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An Assessment of the Impacts of Water Intakes on Alewife, Rainbow Smelt, and Yellow Perch Populations in Lake Michigan

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Argonne, Illinois 60439

AN ASSESSMENT OF THE IMPACTS OF WATER INTAKES
ON ALEWIFE, RAINBOW SMELT, AND YELLOW PERCH POPULATIONS
IN LAKE MICHIGAN

by

S. A. Spigarelli, A. J. Jensen,
and M. M. Thommes

Radiological and Environmental Research Division

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Project Officer: Gary S. Milburn
U. S. EPA Region V, Enforcement Division

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Project Officer: Vacys J. Saulys
U. S. EPA, Great Lakes National Program Office

U. S. Environmental Protection Agency
Great Lakes National Program Office
536 South Clark Street
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FOREWORD

The U.S. Environmental Protection Agency was established to coordinate administration of the major Federal programs designed to protect the quality of our environment. An important part of the Agency's effort involves the search for information about environmental problems, management techniques, and new technologies to optimize use of the nation's land and water resources and minimize the threat pollution poses to the welfare of the American people.

The Great Lakes National Program Office (GLNPO) of the United States Environmental Protection Agency, was established in Region V, Chicago to provide a specific focus on water quality concerns of the Great Lakes. The Great Lakes National Program Office provides funding for studies to address Great Lakes specific environmental concerns and to help fulfill U.S. commitments under the U.S.-Canada Great Lakes Water Quality Agreement of 1978.

This report provides an analysis of fish loss data generated by the electric power generating industry. It is a pioneering effort to utilize water-body wide assessment techniques to address single industry impacts on specific natural resources. We hope that the information and data contained herein will help planners and managers of both the electric power generating industry and regulatory agencies make better decisions for carrying forward their responsibilities.

Madonna F. McGrath
Director
Great Lakes National Program Office

ABSTRACT

A large volume of water is withdrawn from Lake Michigan for cooling and other industrial and municipal purposes. Potential ecological impacts of such withdrawals have caused concern. This study estimates the impacts of entrainment and impingement at water intakes on alewife, smelt, and yellow perch populations of Lake Michigan. Impingement and entrainment estimates were based on data collected by utilities for 316(b) demonstrations at 16 power plants. Two conventional fishery stock assessment models, the surplus production model and the dynamic pool model, were applied to assess the impacts. Fisheries data were applied to estimate the model parameters. Movements related to spawning and seasonal habitat selection cause high variation in impingement and entrainment over time and location. Impingement and entrainment rates were related to geographic location, intake type and position, and volume of water flow. Although the biomass impinged and numbers entrained are large, the proportions of the standing stocks impinged and the proportions of the eggs and larvae entrained are small. The reductions in biomass assuming full flow at all intakes and our estimates of biomass in 1975 are predicted by the models to be: 2.86% for alewife, 0.76% for smelt, and 0.28% for yellow perch.

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SUMMARY

Two factors related to water intakes have indicated the potential for impacts on Lake Michigan fish populations: (1) the present annual water withdrawal (capacity) equals ~260% of the total inshore (depth <10 m) volume of Lake Michigan, and (2) very large numbers of fish are entrapped by water intakes. This study estimates the numbers (and biomass) of alewife, rainbow smelt, and yellow perch that were entrapped in 1975 by all water intakes on Lake Michigan and assesses the impacts of these losses on the three fish populations.

Impingement and entrainment data collected by utilities preparing 316(b) demonstrations were assembled into a computer data base by Argonne National Laboratory. Based on the data collected between 1974 and 1976 at 16 power plant intakes, annual estimates were made of the losses of adults, eggs, and larvae at sampled and unsampled water intakes on Lake Michigan.

Impingement and entrainment of the three species are highly variable processes in time and space, primarily because of population movements related to spawning and seasonal habitat selection.

-In 1975 the lakewide impingement of alewife was ~1.5 million kilograms; about 70% of this total was taken at conventional power plant intakes. Based on previous estimates of alewife standing crop biomass, water intakes impinged a maximum of 1.2% of the 1975 standing crop of alewife. Water intakes on the western shore of Lake Michigan and canal intakes impinged the highest densities (number/unit flow) of alewife.

-Lakewide smelt impingement in 1975 was ~14 thousand kilograms and represented a maximum of 0.1% of the standing crop biomass; about 90% of the lakewide smelt impingement occurred at conventional power plants. Water intakes on the western shore of Lake Michigan impinged the highest densities of smelt.

-A total of ~9.5 thousand kilograms of yellow perch were impinged in 1975 at all water intakes; no estimates of standing crop biomass of yellow perch were available from external sources. Approximately 60% of the lakewide impingement of perch occurred at conventional power plants and 40% were impinged in Green Bay.

-At least 50 billion alewife eggs and one billion alewife larvae were withdrawn in 1975 by all water intakes on Lake Michigan. The majority of alewife eggs and larvae were entrained on Illinois, Indiana, and southwestern Michigan shores. Based on the temporal patterns of entrainment, it appears that planktonic alewife young are transported by counterclockwise currents in the southern basin of Lake Michigan and may "accumulate" in the southern end of the lake.

-Lakewide entrainment of rainbow smelt eggs and larvae were estimated to be 400 million and 50 million, respectively. As with alewife, smelt eggs and larvae seemed to be transported by inshore currents and subsequently entrained at "downstream" intakes, especially on the southern (eggs) and western (larvae) shores of the lake. Smelt eggs and larvae are vulnerable to entrainment for a longer time and by more water intakes than are alewife

eggs and larvae, primarily because smelt have slower development times.

-Although yellow perch eggs and larvae may have been entrained, they were not identified at most sampled intakes. The highest numbers were observed at water intakes on Green Bay and the southeastern shore of Lake Michigan. Approximately 40 million yellow perch eggs and 2 million yellow perch larvae were withdrawn in 1975 by all water intakes.

Three factors apparently affected the impingement and entrainment of the three fish species at sampled water intakes: (1) geographic location; (2) intake type and location, and (3) water flow. Comparisons of mean densities (flow normalization) of each species-lifestage between all sampled intakes grouped by type, indicated that:

-Canal and onshore intakes impinge more alewife/unit volume than do offshore open bay or offshore porous dike intakes.

-Onshore intakes and offshore porous dikes entrain more alewife eggs/unit volume, while offshore open bays entrain higher densities of alewife larvae.

-Canal intakes impinge higher numbers of rainbow smelt/unit volume during the spawning season while offshore intakes impinge higher densities during other periods.

-Offshore intakes entrain more smelt eggs and larvae/unit volume in general.

-The very heterogeneous distribution of yellow perch tended to confound the comparisons between intake types; however, if Green Bay intakes are excluded, offshore open bay intakes seem to impinge high densities of yellow perch. Canal and offshore open bay intakes may be equally destructive of perch eggs and larvae.

-An analysis of the relationships between numbers impinged/entrained and the flows at sampled intakes suggests that ~50% of the variability in impingement and entrainment of each species-life stage is attributable to flow, with the exception of alewife eggs where no relationship was found.

Two mathematical models were applied to (1) describe the dynamics of the impacted fish populations, (2) estimate stock biomass and mortality associated with water withdrawal, and (3) simulate the impact of present and increased water withdrawals. A dynamic pool model and a surplus production model, both standard fishery models, were applied to assess the fish stocks. Different types of data were applied to estimate the parameters of the two models: the surplus production model relies on catch and effort (commercial fishery) data, whereas the dynamic pool model relies on life history data. The results obtained using the different models were quite similar.

-Estimates of standing stock biomass of alewife and rainbow smelt obtained from the models are higher than those obtained from direct sampling of the populations by the Fish and Wildlife Service, but the direct estimates are considered minimum values. Although the biomass estimates in this study could be in substantial error due to parameter assumptions used in the models, even large errors in estimation of biomass would not significantly

alter the conclusions about the impacts of water withdrawal. Standing crop biomass estimates are listed below in the summary table.

- Although the entrainment and impingement coefficients (rates) were low at most sampled intakes, the cumulative impact of total water withdrawal (lakewide) is approaching levels where there may be reason for concern. At total capacity flow for all water intakes, alewife biomass is reduced ~3% and yield to the fishery is reduced ~4%; smelt biomass is reduced ~0.8% and yield is reduced ~1%; yellow perch biomass is reduced ~0.3% and yield is reduced ~0.5%. The impacts on yield to the fishery are higher than the impacts on biomass.
- The impact of impingement was found to be larger than the impact of entrainment, but entrainment impact is more difficult to determine. The impacts of impingement can be assessed using methods that are identical to those applied for fishery assessment and the results appear to be reliable.
- If the reductions in standing stock biomass and yield due to water withdrawal are evaluated as though no other stresses are placed on these fish populations, the impacts are small. Alternatively, if the combined sources of mortality are considered (e.g., predation, fishing, and water withdrawal), and if the liberal stocking of salmonid fishes is taken into account, the mortality of alewife and smelt at water intakes could be viewed as a significant impact on populations that may already be stressed by predation from stocked salmonids. Conversely, the water intake-related losses of alewife and smelt biomass can be viewed as significant losses in the production of salmonid biomass in Lake Michigan.

SUMMARY TABLE

Estimates for 1975	Alewife	Rainbow Smelt	Yellow Perch	
	Lake Michigan Total	Lake Michigan Total	Lake Michigan Total	Green Bay
Maximum impingement (kg)	2.10×10^6	1.86×10^4	1.31×10^4	5.00×10^3
Maximum egg entrainment (number)	7.39×10^{10}	6.15×10^8	4.81×10^7	1.20×10^7
Maximum larval entrainment (number)	1.31×10^9	8.28×10^7	3.26×10^6	2.40×10^6
Standing stock biomass (kg)				
Surplus production model	2.06×10^8	2.53×10^7	1.07×10^7	5.21×10^6
Dynamic pool model	2.37×10^8	2.47×10^7	1.00×10^7	-
U.S. Fish & Wildlife Service	1.22×10^8	1.37×10^7	-	-
Percent reduction in standing stock				
Impingement	2.45	0.46	-	-
Entrainment	0.41	0.30	-	-
Impingement + entrainment	2.86	0.76	0.28	0.61
Maximum sustainable yield (kg)	3.00×10^7	2.50×10^6	7.42×10^5	3.50×10^4
Percentage reduction in MSY				
Impingement	3.42	0.71	-	-
Entrainment	0.56	0.46	-	-
Impingement + entrainment	3.98	1.18	0.47	1.03

INTRODUCTION

As of 1975, the combined capacity for water withdrawal by all power plant, industrial, and municipal water intakes on Lake Michigan exceeded 1.2×10^{13} gal (4.8×10^{10} m³) per year; this volume represents ~260% of the total inshore water (<10 m deep) of the lake. Based on our calculations, all power plant intakes (including Ludington Pump-Storage) have the capacity to withdraw 4.2×10^{10} m³ per year (230% per year) while Ludington has a capacity of 2.1×10^{10} m³ per year (115% per year). Although many intakes are not operated continuously or at full capacity, it is safe to assume that a volume equivalent to the entire inshore volume is withdrawn by water intakes in less than 6 months.

Aside from the considerations of consumptive water use, the withdrawal of such large volumes of inshore water could have biological/ecological impacts since the inshore waters of Lake Michigan serve as spawning areas, migratory routes, and habitats for many species of fish that have commercial, recreational, and trophic importance. Free-swimming adult fishes are subject to entrapment by water intakes, and subsequent impingement on traveling screens. Immature fish (ichthyoplankton) are subject to entrapment and subsequent entrainment into industrial, utility or municipal process streams. Despite efforts to develop intake structures that reduce fish impingement and entrainment, no reductions in intake-related fish mortalities have been affected in Lake Michigan, except for external modifications such as the behavioral barrier placed around the Zion intake.

Numerous species of fish are entrapped by water intakes around Lake Michigan and the populations of many of these fishes have fluctuated greatly in recent years. Numerous factors influence the dynamics of fish populations in Lake Michigan, not the least of which are (1) predation by piscivorous fishes (salmonids) and man; and (2) competition between species with similar niche requirements. It has been hypothesized that the added mortality of fishes at water intakes may constitute a significant stress on some populations, but little effort has been expended to test this hypothesis. CDM/Limnatics [1] conducted a study which estimated the losses of adults, larvae and eggs of every fish species entrapped at 17 power plant intakes on Lake Michigan. These estimates indicated that approximately 93% of the total number of fish impinged were alewife (Alosa pseudoharengus), ~5% were rainbow smelt (Osmerus mordax), and ~0.5% were yellow perch (Perca flavescens). The total biomass impinged of each species was estimated to be 0.06% of the alewife and 0.07% of the smelt standing crops in Lake Michigan in 1974; neither fractional mortality was considered to be stressful.

The present study was designed to provide independent estimates of lake-wide impingement and entrainment-related fish mortalities and an initial assessment of the effects of this additional mortality on the population dynamics of three economically important species: alewife, smelt, and perch. These species were chosen for study because (1) each is important in the fisheries of Lake Michigan, (2) alewife and smelt are critical forage species for the huge numbers of salmonid fishes introduced into the lake, and (3) each species suffers large intake-related mortalities at some or all of the water intakes on Lake Michigan.

The objectives of this study were to (1) collect extant data on fish

impingement and entrainment at sampled power plant intakes and estimate mortalities at all unsampled intakes, thereby developing a lakewide data base; (2) compare species-specific losses between intake types and locations on Lake Michigan; (3) compare the losses of each species with previous (1975) and present estimates of population standing crop biomass; and (4) simulate the effects of intake-related fish mortality on species' production, standing crop, and yield to the fishery. In all calculations, it was assumed that all entrapped adults, larvae and egg die, i.e., a worse case assessment.

The impact of entrainment and impingement cannot be assessed directly. To determine the proportion of a population that is impinged or entrained, the number or biomass of the impacted population must be known or estimated. Direct estimates of abundance are difficult and costly for large populations, so a mathematical model was applied to estimate fish abundances in Lake Michigan using commercial catch and effort data. Mathematical models also were applied to simulate the impact on standing stocks and yields under existing and increased water withdrawals from Lake Michigan.

Models applied for power plant assessment have not been of the same form as models applied for assessment of the impact of fishing on fish populations. Models constructed by persons with engineering backgrounds are often linear compartment types that do not adequately represent the biology or have poorly defined biological variables that are difficult to estimate. The models most commonly used by biologists are of the Leslie-matrix type [2-6]. These models are useful for population projection and consider the population age structure; but application requires estimation of a large number of parameters that are difficult to estimate. Also, these models require specification of compensation mechanisms and this aspect has been controversial [7]. Finally, this approach requires good estimates of mortality and growth for early life history stages. Swartzman, Deriso, and Cowan [8] have critically compared several models applied for power plant impact assessment. A major difficulty for workers in environmental impact assessment is that, typically, results are required at once and there is little time to gain experience with different methods.

In fisheries studies three models have been developed for assessment of the impact of fishing. These models were developed between the late 1920's and early 1960's, a period of 30 years. Development of these models was slow and it was accompanied by the development of an understanding of the problems of parameter estimation and of how to work with less than a complete understanding of how fish populations compensate for fishing. The three models are usually termed the surplus production model, dynamic pool model, and spawner-recruit model.

Surplus production models relate the biomass and productivity of the stock directly to yield. These are the simplest to develop and apply, but many assumptions are necessary. Application to laboratory and wild fish populations indicates that this type of model is useful for estimation of population abundance and for determining the level at which a population is being exploited [9].

The dynamic pool model is now the most widely applied type for stock assessment. This model combines data on growth, reproduction, and mortality and is both flexible and easy to apply. Structurally, the dynamic pool model

is more readily understood than the surplus production model, and it can be expanded easily to include new information. Application of dynamic pool models requires a considerable amount of information on growth and age structure.

Spawner-recruit models have been applied in power plant impact assessment studies [7], but they were developed for salmon populations exhibiting clear spawner-recruit relationships, where data for numbers of spawners and recruits are obtainable. For most species, estimates of numbers of spawners and recruits are difficult to obtain, and no clear relationship between the number of spawners and the number of recruits is detectable.

In this study both the surplus production model and the dynamic pool model are applied to estimate the biomass of the population, number of eggs produced, and number of larvae produced. These estimates are applied to determine the proportions of each population impinged and entrained, and then to estimate coefficients of entrainment and impingement. The models are applied to examine the impact on standing stock, biomass, and yield of fish populations due to present and increased rates of water withdrawal.

The surplus production model and dynamic pool model apparently have not been applied for power plant assessment but several components of the dynamic pool model have been applied [10-13]. Application of fisheries models for the assessment of environmental impact takes advantage of the considerable experience gained through the assessment of the impact of fishing on fish populations. Application of the surplus production model and dynamic pool model together for power plant assessment gives a degree of confidence in the results that is not attained with application of either model alone. The two models are entirely different structurally and the data for parameter estimation in the two models are entirely different. Close agreement between the results of the two simulations with different models would constitute "independent" corroboration of the assessment.

For estimation of power plant-related model parameters, full design volume flow has been assumed and numbers and biomass entrained or impinged have been extrapolated to design flow conditions.

ACQUISITION AND DEVELOPMENT OF THE DATA BASE

Sampled Power Plants

This study relied exclusively on extant data provided by the various electric utilities that conducted 316(b) studies and by federal/state resource agencies. Fish impingement data initially were obtained for a study of impingement throughout the United States [14]; entrainment data were obtained subsequently and added to the data base. Since variations in daily flow rates are common, especially at coal-fired power plants that are operated in a peaking mode, we obtained daily average flow rates for each of the sampled plants during their respective periods of impingement and entrainment sampling.

The impingement and entrainment data bases exist as permanent batch-only-accessible data sets. They reside within the large capacity pool of Itel

7330-12 storage disc drives shared by Argonne National Laboratory's IBM 370/195 and IBM 3033 computer systems. Statistical analyses were performed using the Statistical Analysis System (SAS 79.2B version) [15]. Graphical output was achieved by using an interface (SASMYPLT) [16] between the SAS package and the PLOTIN/MYPLT [17] general purpose plotting program. This interface, developed by the Radiological and Environmental Research Division, results in the production of publishable quality graphics.

Table 1 summarizes the design characteristics and sampling intervals for 16 power plants and Figure 1 shows the locations of these plants on Lake Michigan. Unfortunately, neither the sampling schedules nor the methods were standardized among plants. Most plants were sampled for impingement during the major portion of 1975, except for Bailly, Michigan City, Campbell, Palisades, and Big Rock; only two plants (Zion and Cook) were sampled for two consecutive years, providing some temporal comparison. The most common schedule was to collect an integrated sample (<24 hours) every fourth day; only one plant (Cook) was sampled daily for impingement. Entrainment sampling was initiated in 1975 at all but one plant (Big Rock) and continued for less than one year at all plants except Cook, Bailly, Campbell, and Big Rock where at least one full year of data were collected. Most plants were not sampled for entrainment from January through March. The most common schedules of entrainment sampling were every fourth day or once per week, and most plants were sampled in the intake stream.

It is difficult to evaluate the effects of variable methods on the estimation of fish impingement or entrainment as reported by the utilities; we made no attempt to normalize data for these potential sources of variance. Murarka et al. [18] compared various impingement sampling designs and concluded that the stratified-systematic scheme is superior to the systematic-random sampling scheme used by most of the utilities on Lake Michigan.

Power plant data sets that spanned less than one full year were extrapolated to a full year by assuming a linear reduction from the last data entry to zero at the end of the year and/or linear extrapolation from zero to the first data entry for the year. This procedure allowed the estimation of annual impingement and entrainment values for all sampled power plants.

If samples were not collected daily (all plants except Cook), missing daily values were estimated (interpolated) by means of the following equation:

$$I_{i+s} = (A_i + sR_{i,j}) \times f_{i+s} \text{ for } s = 1, 2, \dots, j-i \text{ (} j-i > 0 \text{)}$$

where

$$R_{i,j} = \frac{A_j - A_i}{j - i} \text{ for all } j > i.$$

A_i, A_j = observed impingement/entrainment rates for the $i^{\text{th}}, j^{\text{th}}$ days.
 I_{i+s} = impingement/entrainment value for $(i+s)^{\text{th}}$ missing observation.
 f_{i+s} = water intake flow rate for the $(i+s)^{\text{th}}$ missing observation.

Table 1. Intake sampling and design characteristics for 16 sampled power plants on Lake Michigan.

Plant (ID)	Approx. MWe	Intake Design	Maximum Flow (m ³ /yr)	Impingement Sampling Dates	Schedule	Entrainment Sampling Dates	Schedule	Location
Zion (1)	2100	OOB ^a	3.48 x 10 ⁹	02/28/74-12/31/75	every 4th day	04/16/75-09/17/75	1/week	discharge/intake
D. C. Cook (2)	2200	OOB	3.27 x 10 ⁹	02/01/75-12/30/76	daily	01/01/75-12/31/75	daily	discharge
Bailly (3)	615	PD	6.70 x 10 ⁸	11/07/75-11/10/76	every 4th day	11/07/75-11/10/76	every 4th day	discharge/intake
Michigan City (4)	715	CNL	5.97 x 10 ⁸	12/03/75-06/28/76	every 4th day	N/A ^c	N/A	N/A
Pulliam (5)	390	CNL	7.75 x 10 ⁸	04/04/75-03/22/76	every 4th day	04/09/75-08/27/75	24 hrs/week	discharge/intake
Kewaunee (6)	525	OOB	8.22 x 10 ⁸	04/01/75-03/17/76	every 4th day	04/01/75-12/15/75	1/week	intake
Point Beach (7)	1030	PD	1.53 x 10 ⁹	03/04/75-02/28/76	every 4th day	04/18/75-10/31/75	every 4th day	intake
Port Washington (8)	400	CNL	1.09 x 10 ⁹	03/03/75-02/25/76	every 4th day	04/15/75-10/28/75	every 4th day	intake
Lakeside (9)	345	PD	8.73 x 10 ⁸	03/07/75-02/06/76	every 4th day	05/20/75-10/29/75	every 4th day	intake
Oak Creek (10)	1670	CNL	2.45 x 10 ⁹	03/04/75-02/27/76	every 4th day	04/17/75-10/30/75	every 4th day	intake
Waukegan (11)	1100	CNL	1.43 x 10 ⁹	05/12/75-04/28/76	every 4th day	04/16/75-09/03/75	1/week	discharge/intake
Stateline (12)	960	PD	1.65 x 10 ⁹	04/05/75-03/30/76	every 4th day	04/05/75-09/04/75	every 4th day	discharge
D. Mitchell (13)	415	PD	8.23 x 10 ⁸	05/03/75-04/27/76	every 4th day	05/03/75-09/20/75	every 4th day	discharge/intake
J. H. Campbell (14)	645	CNL	5.97 x 10 ⁸	Jan 74-Mar 75	24 hrs/week	01/29/75-03/24/76	24 hrs/week	intake
Palisades (15)	840	OOB	1.19 x 10 ^{8b}	Mar 74-Mar 75	24 hrs/week	03/27/75-02/03/76	24 hrs/week	intake
Big Rock (16)	75	PD	9.55 x 10 ⁷	Feb 74-Mar 75	24 hrs/week	02/07/74-03/19/75	24 hrs/week	intake

^a OOB = offshore open bay; PD = porous dike; CNL = canal.

^b All plants operate once-through except Palisades which utilizes cooling towers.

^c Entrainment information reported for Michigan City not useful for this analysis.

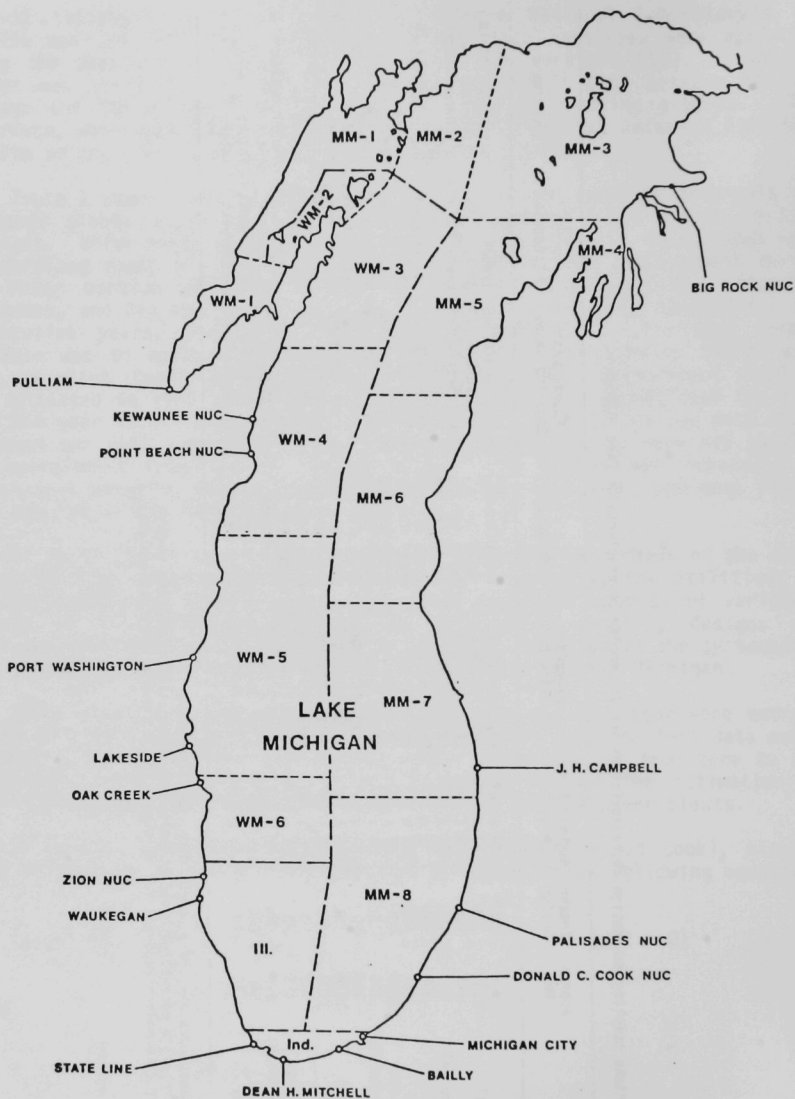


Fig. 1. Map of Lake Michigan showing locations of sampled power plants and statistical districts.[1]

This method provides a weighted linear interpolation between successive observations on impingement and entrainment variables. The impingement/entrainment processes are approximated by linear segments.

Entrainment data for D. C. Cook were received in a reduced form where numbers of each fish group were reported as totals for irregular time periods. These totals were divided by the number of days in the sample period, thereby producing average daily values for the period. No useful entrainment data were obtained from the Michigan City plant; therefore, Michigan City was treated as an unsampled plant for entrainment calculations.

Observed, interpolated, and extrapolated daily values were summed by month and year for each sampled plant. For each of the three species, numbers and weights impinged, and number of eggs and larvae entrained were calculated. These totals were termed "observed" values even though missing daily values were estimated by interpolation and extrapolation. Age classes or size distribution of impinged fishes were not reported for most power plants. Egg and larval categories were used for entrainment because no standard categories were reported by the various utilities. Some utility reports identified larval and "juvenile" stages; in these cases, both categories were considered to be larvae.

Egg entrainment data for D. C. Cook were reported as a total for the three species (i.e., no egg identification was made). Species totals were estimated assuming 90% of the total to be alewife eggs, 4% to be smelt eggs, and 1% to be perch eggs [19]. A similar problem was encountered with the Pulliam egg entrainment data except egg diameters were reported. In this case, we estimated the fractional species total by assuming ranges in egg diameters for each species during the time periods that each would be expected to spawn (e.g., smelt eggs = 0.6-1.3 mm, April-May; alewife eggs = 0.6-1.3 mm, June-July; yellow perch = 1.6-2.3 mm, May-June).

Using the "observed" daily data for each sampled plant, we generated the data base which estimates the monthly and annual totals by fish category and by plant for the sampling periods, based on actual flows. An "extrapolated" data base was generated which estimates the maximum impingement/entrainment losses as if all plants had operated at maximum (capacity) cooling water flow rate over the full year. These extrapolations were based on the ratios of actual/design flows.

Unsampled Intakes

Since the impingement/entrainment data base only represents fish losses at 16 of the 22 power plants on Lake Michigan and does not include estimates for other water intakes sited on the lake, we developed a list of all other intakes and their capacity flows (Table 2). Assuming capacity flow throughout the year, we estimated the annual impingement and entrainment values for unsampled intakes by multiplying the mean impingement and entrainment rates at all sampled plants in the same region (statistical district) by the capacity flows at unsampled intakes.

Although we considered methods of estimation that would account for the influence of intake type and spatial heterogeneity in fish abundances, the extant information on unsampled intakes [20] is not very descriptive of design

Table 2. Locations and design flows of unsampled water intakes on Lake Michigan. [20]

Plant Name	Plant Type	Statistical District	Design Flow	
			(gal/min)	(m ³ /min)
Lake City Public Water Department	MUN	ILL	1,389	5
UTI	ILL		6,944	26
Waukegan Water Utility	IND	ILL	1,389	5
Johns-Manville Products	IND	ILL	2,244	8
US Steel Works	IND	ILL	2,778	11
Johnson Outboards	IND	ILL	11,111	42
Abbott Laboratories	MUN	ILL	2,431	9
City of North Chicago	MUN	ILL	4,167	16
Great Lakes Naval Station	MUN	ILL	2,083	8
City of Lake Forest	MUN	ILL	521	2
Fort Sheridan-US Army DFAE	MUN	ILL	278	1
Highwood Water Plant	MUN	ILL	5,729	22
Highland Water Plant	MUN	ILL	1,319	5
Village of Glencoe	MUN	ILL	2,222	8
Mark Dalin Memorial Plant	MUN	ILL	2,639	10
Village of Winnetka	MUN	ILL	311	1
Kenilworth Water Filtration Plant	MUN	ILL	5,208	20
Wilmette Water Works	MUN	ILL	16,667	63
City of Evanston Water and Sewer Dept	MUN	ILL	709,023	2,684
City of Chicago Dept Water and Sewer	MUN	ILL	139	1
John G Shedd Aquarium	MUN	ILL	18,055	68
Hammond Water Dept	IND	IND	3,819	14
Lever Bros Co	MUN	IND	1,042	4
Whiting Filtration Plant	IND	IND	9,028	34
American-Maize Prod Co	IND	IND	92,361	350
American Oil Co-Whiting Refinery	MUN	IND	11,805	45
East Chicago Water Dept	IND	IND	749,997	2,839
Inland Steel Co	IND	IND	318,748	1,207
Youngstown Sheet and Tubing	MUN	IND	20,833	79
Gary-Hobart Water Corp	IND	IND	69,120	262
Union Carbide-Linde Div	IND	IND	2,244	8
Universal Atlas Cement	IND	IND	568,669	2,153
US Steel	IND	IND	17,361	66
Midwest Steel	IND	IND	305,000	1,155
Bethlehem Steel-Burns Harbor	MUN	IND	5,000	19
Michigan City Dept of Water Works	IND	IND	449	5
American Playground and Device Co	MUN	IND	1,389	5
Escanaba Mun Water Utility-Sand Point	IND	IND	20,833	79
Mead Paper Co	UTI	IND	16,667	63
Escanaba Generating Station	MUN	IND	1,500	6
Gladstone Water Treatment	UTI	IND	3,600	14
Gladstone Generating Station	MUN	IND	1,181	4
City of Menominee	IND	IND	5,000	19
Inland Lime and Stone Co	MUN	IND	494	2
City of Michiana	MUN	IND	1,391	5
City of New Buffalo	MUN	IND	404	2
City of Bridgman	MUN	IND	4,200	16
St Joseph Water Filtration Plant	MUN	IND	4,167	16
City of Benton Harbor Water Dept	MUN	IND	1,389	5
South Haven Water Treatment Plant	MUN	IND	4,444	17
Holland Water Treatment Plant	MUN	IND	10,903	41
Wyoming Water Treatment Plant	MUN	IND	24,305	92
City of Grand Rapids	MUN	IND	5,835	22
City of Grand Haven Water Treatment Plant	MUN	IND	294	1
Muskegon Hts Water Treatment Plant	MUN	IND	7,639	29
City of Muskegon Water Treatment Plant	MUN	IND	2,082	8
Ludington Water Filtration Plant	MUN	IND	29,668,626	112,309
Ludington Pump-Storage Facility	UTI	IND	3,472	13
City of Traverse City	MUN	IND	13,194	50
Bayside City Light and Power Co	UTI	IND	1,795	7
Medusa Portland Cement	IND	IND	1,346	5
Penn-Dixie Cement Corp	MUN	IND	1,389	5
Marinette Water Works	MUN	IND	10,764	41
Green Bay Water Dept	MUN	IND	5,555	21
Two Rivers Water and Light Dept	MUN	IND	13,465	51
Manitowoc Public Utilities	UTI	IND	9,028	34
Manitowoc Power Plant	MUN	IND	131,956	500
Sheboygan Water Utility	MUN	IND	15,260	58
Edgewater Power Plant	UTI	IND	4,167	16
City of Glendale	MUN	IND	116,367	441
City of Pt Washington Filtration Plant	MUN	IND	4,028	15
City of Milwaukee	MUN	IND	3,125	12
North Shore Water Commission	MUN	IND	4,514	17
Univ of Wis-Milwaukee-Central Plant	MUN	IND	2,778	11
Cudahy Water Utility	MUN	IND	15,833	60
South Milwaukee Water Utility	MUN	IND	12,068	46
Racine Water Dept	MUN	IND		
Kenosha Water Utility	MUN	IND		

and the available data on fish abundances do not have the necessary spatial definition. Some sampling of adult fish and ichthyoplankton in inshore waters was performed at each power plant required to do 316(b) studies, but the methods and periods of sampling were not standardized between locations. Consequently, utility data on fish abundances could not be compared between intake sites and were not useful for adjusting impingement/entrainment rates, based on fish abundance.

Lakewide estimates of impingement and entrainment-related mortalities of alewife, smelt, and yellow perch are reported as totals for (1) all power plant intakes excluding the Ludington Pump-Storage Power Plant; (2) all power plant intakes including Ludington; (3) all other intakes; and (4) all intakes on Lake Michigan. These results provide the only estimates of total intake-related fish mortalities for Lake Michigan, albeit 6 years after the fact.

IMPINGEMENT ESTIMATES

Alewife Impingement - Sampled Intakes

Impingement rates of alewife at the 16 sampled power plants were strongly dependent on time of year and location in Lake Michigan. Maximum impingement of alewife occurred from May through July, with the largest numbers (1.93×10^7) and biomass (7.03×10^5 kg) impinged in May (Table 3). Approximately 95% (1.8×10^7) of the May 1975 impingement occurred at the Zion plant and this inordinately high value was the direct result of a delay in the positioning of a behavioral barrier (screen) around the intake [1]; in 1974, the screen was in place in May and the numbers of alewife impinged that month at Zion was $\sim 3.8 \times 10^5$. It is evident that the high impingement rates in early summer reflect the inshore spawning migrations of adult alewife rather than seasonal changes in total cooling water flow. Likewise, the reductions in alewife impingement from December through March reflect the offshore movement of the alewife population during early winter. A small peak in alewife impingement occurred in October and November prior to the winter migration offshore.

The annual total alewife impingement at the sampled power plants was estimated to be 2.67×10^7 (9.17×10^5 kg). Almost 90% of this total was impinged at four of the 16 sampled power plants (Table 4): 69% at Zion (1.83×10^7), 9% at Port Washington (2.41×10^6), 6% at Oak Creek (1.70×10^6), and 4% at Point Beach (1.19×10^6). Figures A.1.a-A.16.a (Appendix A) show the daily densities of alewife impinged at each sampled plant. The maximum daily densities were <10 alewife/1000 m^3 at all plants except Zion and Port Washington where the maximum densities were 400 and 40 alewife/1000 m^3 , respectively. Relatively high impingement densities (>0.1 alewife/1000 m^3) were sustained between April and November at five of the sampled plants: Zion, Waukegan, Port Washington, Point Beach, and Kewaunee. These plants have no common attributes other than their locations on the western shore of Lake Michigan. The combination of relatively high alewife densities and total flows resulted in the disproportionate impingement of alewife at a few plants on the western shore. The relatively low impingement densities at the plants sited on the eastern shore (Cook, Palisades, Campbell, and Big Rock) probably reflect a general trend toward lower alewife densities along this shore.

The timing of the major influx of alewife (rapid increase in impingement)

Table 3. Estimated total number and biomass of alewife, rainbow smelt, and yellow perch impinged each month at all 16 sampled power plants (1975).

	Total Flow m ³	Alewife		Smelt		Perch	
		Number	Kg	Number	Kg	Number	Kg
January	8.57 x 10 ⁸	8.08 x 10 ²	2.10 x 10 ¹	1.34 x 10 ⁴	2.31 x 10 ²	6.99 x 10 ³	8.20 x 10 ¹
February	7.39 x 10 ⁸	4.82 x 10 ²	1.20 x 10 ¹	1.18 x 10 ⁴	3.18 x 10 ²	2.82 x 10 ³	6.80 x 10 ¹
March	7.88 x 10 ⁸	2.47 x 10 ⁴	7.46 x 10 ²	3.05 x 10 ⁴	1.24 x 10 ³	3.95 x 10 ³	9.50 x 10 ¹
April	9.01 x 10 ⁸	6.08 x 10 ⁵	2.53 x 10 ⁴	1.41 x 10 ⁵	2.13 x 10 ³	5.55 x 10 ³	3.56 x 10 ²
May	1.02 x 10 ⁹	1.93 x 10 ⁷	7.03 x 10 ⁵	4.61 x 10 ⁴	5.23 x 10 ²	7.89 x 10 ³	5.27 x 10 ²
June	9.93 x 10 ⁸	3.83 x 10 ⁶	1.09 x 10 ⁵	3.58 x 10 ⁴	4.88 x 10 ²	1.89 x 10 ³	1.52 x 10 ²
July	1.16 x 10 ⁹	1.69 x 10 ⁶	4.48 x 10 ⁴	1.22 x 10 ⁵	1.24 x 10 ³	2.60 x 10 ³	2.70 x 10 ²
August	1.18 x 10 ⁹	4.75 x 10 ⁵	1.40 x 10 ⁴	9.03 x 10 ⁴	7.33 x 10 ²	1.83 x 10 ³	1.52 x 10 ²
September	1.05 x 10 ⁹	1.06 x 10 ⁵	3.00 x 10 ³	6.91 x 10 ⁴	4.46 x 10 ²	2.03 x 10 ³	8.80 x 10 ¹
October	1.09 x 10 ⁹	1.77 x 10 ⁵	3.74 x 10 ³	1.23 x 10 ⁵	6.96 x 10 ²	6.26 x 10 ⁴	6.27 x 10 ²
November	9.63 x 10 ⁸	1.94 x 10 ⁵	1.92 x 10 ³	4.61 x 10 ⁴	5.42 x 10 ²	2.79 x 10 ⁴	4.62 x 10 ²
December	9.62 x 10 ⁸	2.15 x 10 ⁴	3.86 x 10 ²	3.48 x 10 ⁴	1.05 x 10 ³	1.05 x 10 ⁴	1.53 x 10 ²
Total observed	1.17 x 10 ¹⁰	2.65 x 10 ⁷	9.07 x 10 ⁵	7.64 x 10 ⁵	9.63 x 10 ³	1.37 x 10 ⁵	3.03 x 10 ³
Estimated annual total	-	2.67 x 10 ⁷	9.17 x 10 ⁵	7.69 x 10 ⁵	9.77 x 10 ³	1.39 x 10 ⁵	3.11 x 10 ³

Table 4. Estimated total number and biomass of alewife, rainbow smelt, and yellow perch impinged annually at each of the sampled power plants on Lake Michigan (1975).

	Total Flow m ³	Alewife		Smelt		Perch	
		Number	Kg	Number	Kg	Number	Kg
Zion	2.04 x 10 ⁹	1.83 x 10 ⁷	6.80 x 10 ⁵	5.80 x 10 ⁴	2.48 x 10 ³	5.85 x 10 ²	6.90 x 10 ¹
Cook	1.32 x 10 ⁹	1.73 x 10 ⁵	5.11 x 10 ³	4.11 x 10 ³	5.10 x 10 ¹	1.28 x 10 ⁴	3.97 x 10 ²
Bailly	4.71 x 10 ⁸	1.21 x 10 ⁵	4.52 x 10 ³	7.54 x 10 ²	1.70 x 10 ¹	6.66 x 10 ²	4.40 x 10 ¹
Michigan City	1.01 x 10 ⁸	1.03 x 10 ⁵	N/A	3.23 x 10 ²	N/A	2.89 x 10 ²	N/A
Pulliam	3.34 x 10 ⁸	5.78 x 10 ⁵	2.46 x 10 ⁴	7.30 x 10 ³	2.73 x 10 ²	1.18 x 10 ⁵	2.14 x 10 ³
Kewaunee	6.70 x 10 ⁸	1.79 x 10 ⁵	4.84 x 10 ³	1.91 x 10 ⁴	4.75 x 10 ²	2.40 x 10 ²	4.00 x 10 ¹
Point Beach	1.21 x 10 ⁹	1.19 x 10 ⁶	3.74 x 10 ⁴	1.76 x 10 ⁵	1.26 x 10 ³	2.55 x 10 ²	3.90 x 10 ¹
Port Washington	5.74 x 10 ⁸	2.41 x 10 ⁶	6.11 x 10 ⁴	7.79 x 10 ⁴	8.95 x 10 ²	2.62 x 10 ²	2.30 x 10 ¹
Lakeside	2.64 x 10 ⁸	4.79 x 10 ⁴	1.40 x 10 ³	1.19 x 10 ²	2.00 x 10 ⁰	1.80 x 10 ¹	3.00 x 10 ⁰
Oak Creek	1.64 x 10 ⁹	1.70 x 10 ⁶	3.29 x 10 ⁴	4.09 x 10 ⁵	3.76 x 10 ³	1.43 x 10 ³	1.06 x 10 ²
Waukegan	9.32 x 10 ⁸	7.66 x 10 ⁵	2.80 x 10 ⁴	9.81 x 10 ³	3.77 x 10 ²	3.21 x 10 ²	3.80 x 10 ¹
Stateline	1.02 x 10 ⁹	6.57 x 10 ⁵	2.19 x 10 ⁴	8.55 x 10 ²	2.30 x 10 ¹	1.24 x 10 ³	8.20 x 10 ¹
Mitchell	5.11 x 10 ⁸	1.46 x 10 ⁵	3.68 x 10 ³	3.25 x 10 ²	4.00 x 10 ⁰	5.16 x 10 ²	4.60 x 10 ¹
Campbell	4.17 x 10 ⁸	4.54 x 10 ⁴	1.10 x 10 ³	5.39 x 10 ²	1.07 x 10 ¹	3.42 x 10 ²	7.14 x 10 ⁰
Palisades	1.22 x 10 ⁸	3.14 x 10 ²	1.22 x 10 ¹	1.40 x 10 ¹	2.27 x 10 ⁻¹	1.10 x 10 ¹	1.13 x 10 ⁻¹
Bfg Rock	8.20 x 10 ⁷	9.50 x 10 ¹	3.51 x 10 ⁰	1.28 x 10 ²	2.38 x 10 ⁰	1.70 x 10 ¹	2.04 x 10 ⁰
Total observed	1.17 x 10 ¹⁰	2.65 x 10 ⁷	9.07 x 10 ⁵	7.64 x 10 ⁵	9.63 x 10 ³	1.37 x 10 ⁵	3.03 x 10 ³
Estimated annual total	-	2.67 x 10 ⁷	9.17 x 10 ⁵	7.69 x 10 ⁵	9.77 x 10 ³	1.39 x 10 ⁵	3.11 x 10 ³

in the spring was highly dependent on latitudinal location. Plants on the southern basin of the lake experienced initial high impingement densities in March or April while those on the northern basin experienced alewife influxes during late April and May. This apparent locational effect on the timing of inshore migrations is undoubtedly linked to the different inshore warming rates between north and south locations. The Pulliam plant was somewhat unique in that no alewife were impinged until mid-May, indicating a complete absence of alewife from southern Green Bay between January and April, and a massive influx in May.

Although most plants impinged very few alewife during the winter months, relatively high and sustained densities of alewife were impinged during winter at Port Washington, Waukegan, and Zion and less frequently at other plants. Only the Pulliam, Lakeside, Oak Creek, and Big Rock plants did not impinge alewife during mid-winter. Impingement totals during winter months (Table 3) were relatively low compared with other seasons but the indication of periodic inshore movements or continued inshore residence by alewife during winter is rather enigmatic. Table 5 summarizes the mean weights of alewife impinged each month and year at the sampled plants. The mean weights of alewife impinged during winter months were often greater than during other months, indicating that the largest/oldest alewife either (1) tend to precede the general population in the spring spawning migration, or (2) that some larger alewife tend to remain/migrate inshore during the winter. The mean weights of alewife impinged during and after the major spawning runs tended to decrease with time (May through November), indicating a size-related timing to the spawning migration or to inshore distributions of alewife. This relationship may be a function of size-related temperature preferences [21] and the natural temperature cycle of inshore waters.

Secondary peaks in alewife impingement occurred in the fall at about half of the sampled plants (Figs. A.1.a-A.16.a), with no apparent effect of location on the occurrence of this fall peak. Beginning in September 1974, October 1975, and September 1976 (Table 5) the lakewide mean weights of impinged alewife decreased markedly and remained low for 2-3 months each year, reflecting the predominance of very small alewife (5-10 g), presumably young of the year (YOY). Most plants that experienced fall peaks in alewife impingement showed concurrent decreases in mean weights of alewife, implying offshore to inshore movements by YOY alewife at that time and location. Lakeside (Fig. A.9.a) and Zion (Fig. A.1.a) impinged substantial numbers of alewife in the fall of 1975, but showed minimal decreases in mean weights of impinged fish; however, Zion experienced a major influx of YOY alewife in the fall of 1974.

Although the evidence in Table 5 is equivocal, the lakewide average weights of alewife may have increased between 1974 and 1976. Zion data indicate an increase between 1974 and 1975, while Cook data indicate a decrease between 1975 and 1976. The annual mean weights of alewife impinged at each plant tended to range between 24 and 37 g, while those at Pulliam (42.5 g) and Oak Creek (19.3 g) apparently were extreme values.

Alewife Impingement - Lakewide

Based on the observed impingement rates at the 16 sampled power plants, the maximum annual lakewide impingement of alewife at all water intakes was

Table 5. Mean weights (g) of alewife impinged each month at 15 power plants on Lake Michigan, 1974-1976. Dashes indicate sampling but no alewife impinged.

Plant (ID)	Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Annual Mean Weights
Zion (1)	1974			41.2	40.5	39.5	35.3	28.7	28.8	22.9	23.1	14.8	29.3	31.6
	1975	16.2	46.1	54.6	44.7	37.0	32.8	27.9	28.9	21.1	18.1	31.3	32.5	37.1
Cook (2)	1975		5.4	30.2	37.6	34.9	24.9	24.8	24.5	18.0	5.2	23.1	41.4	29.6
	1976	50.9	36.7	43.4	40.8	30.1	24.7	25.4	22.7	6.7	5.2	25.1	26.1	26.2
Bailly (3)	1975											11.0	23.8	37.4
	1976	32.4	13.9	56.5	43.4	43.8	35.9	31.5	25.1	15.5	6.3	24.1		
Pulliam (5)	1975				-	38.6	43.7	49.7	40.2	39.4	24.7	2.7	16.2	42.5
	1976	-	-	-										
Kewaunee (6)	1975				27.0	29.5	32.0	31.4	28.7	28.9	23.4	12.3	-	27.6
	1976	45.0	72.0	62.0										
Point Beach (7)	1975			-	36.6	32.2	33.9	34.6	33.3	23.8	6.1	5.3	32.1	31.4
	1976	33.1	34.0											
Port Washington (8)	1975			28.2	40.5	24.9	27.2	21.4	31.2	18.4	6.5	20.7	21.4	25.3
	1976	20.5	20.3											
Lakeside (9)	1975			-	3.5	23.9	28.6	38.4	28.9	32.0	23.3	20.5	27.0	29.3
	1976	-	-											
Oak Creek (10)	1975			36.8	31.7	28.1	19.1	13.0	19.3	13.4	14.9	18.4	18.6	19.3
	1976	-	-											
Waukegan (11)	1975					31.8	23.2	17.1	30.1	19.2	7.6	8.3	2.7	26.5
	1976	37.2	53.3	48.9	35.3									
State Line (12)	1975				41.6	37.1	29.1	24.6	16.6	37.6	22.4	12.6	41.8	33.6
	1976	30.1	-	-										
Mitchell (13)	1975					39.1	26.9	26.1	30.0	17.9	6.6	2.1	12.0	25.6
	1976	105.7	23.0	-	30.7									
Campbell (14)	1974	-	-	22.7	37.4	37.4	27.8	26.1	15.2	8.2	6.4	6.4	7.4	24.1
	1975	-	-											
Palisades (15)	1974			46.7	43.7	30.0	38.1	35.2	29.3	-	-	-	-	39.0
	1975	-	32.4											
Big Rock (16)	1974			-	-	35.6	35.7	41.3	37.8	-	-	-	-	37.0
	1975	-	-	-										
<u>Σ Mean Weights</u>	1974	-	-	36.9	40.5	35.6	34.2	32.8	27.8	15.6	14.8	10.6	18.4	26.7
<u>n Plants</u>	1975	16.2	39.3	37.5	32.9	32.5	29.2	28.1	28.3	24.5	14.4	14.0	24.2	26.8
	1976	44.4	36.2	52.7	37.6	37.0	30.3	28.5	23.9	11.1	5.8	24.6	26.1	29.9

estimated to be 6.18×10^7 (2.10×10^6 kg)(Table 6). Since this estimate is based on the assumption that all intakes were operated continuously at maximum capacity, it is an over-estimate of the annual lakewide impingement. The total observed flow at the 16 sampled power plants in 1975 (1.17×10^{10} m³) was ~58% of capacity flow (2.03×10^{10} m³) and probably is representative of annual water usage by all conventional power plants. Other intakes on Lake Michigan probably are operated at or near capacity flows. It follows that the actual lakewide impingement of alewife in 1975 was on the order of 1.5×10^6 kg. Approximately 70% of the annual total alewife impingement occurred at conventional power plants, despite the fact only 43% of the total flow was used by these power plants. The reasons for this anomaly are: (1) Zion's inordinate impingement rate in 1975 and (2) the relatively low estimated density of alewife in the region of the Ludington Pump Storage Plant.

Table 6. Estimated total numbers and biomass (kg) of alewife, smelt, and yellow perch impinged at sampled power plants, unsampled power plants, and municipal/industrial intakes on Lake Michigan, assuming design flow operation (1975).

	Total Flow (m ³)	Alewife		Smelt		Perch	
		Number	Kg	Number	Kg	Number	Kg
16 sampled power plants	2.03×10^{10}	4.53×10^7	1.55×10^6	1.18×10^6	1.55×10^4	3.13×10^5	6.70×10^3
Unsampled power plants	3.70×10^8	8.80×10^5	2.35×10^4	2.77×10^4	3.21×10^2	1.13×10^2	1.14×10^1
Total conventional plants	2.07×10^{10}	4.62×10^7	1.57×10^6	1.21×10^6	1.58×10^4	3.13×10^5	6.71×10^3
Ludington P.S. plant	2.11×10^{10}	2.53×10^6	7.50×10^4	6.03×10^4	7.56×10^2	1.88×10^5	5.81×10^3
Total all power plants	4.18×10^{10}	4.87×10^7	1.65×10^6	1.27×10^6	1.66×10^4	5.01×10^5	1.25×10^4
Total municipal/industrial	6.51×10^9	1.31×10^7	4.56×10^5	8.53×10^4	2.07×10^3	1.60×10^4	6.20×10^2
Total all intakes	4.83×10^{10}	6.18×10^7	2.10×10^6	1.36×10^6	1.86×10^4	5.17×10^5	1.31×10^4

The total annual impingement of alewife in each statistical district is given in Table 7. The mean densities of impinged alewife were highest in Illinois > WM5 > WM1; all of these regions are on the western side of the lake. The highest total volumes of water are withdrawn in districts MM6 > Indiana > Illinois > MM8 although the highest numbers were impinged in Illinois > WM5 > Indiana. Thus, no clear relationship exists between total flow and estimated total alewife impingement in statistical districts.

The estimates given in Table 7 should be interpreted and used with caution. In statistical districts where no sampling was performed (e.g., MM4), the observed density from an adjacent district (MM3) was applied to calculate the numbers impinged (i.e., assumed density x flow = estimated number). In the case of unsampled intakes within districts where some sampling was performed, the estimates seem to be reasonable. Table 8 presents a comparison of our estimates for three intakes that were classified as unsampled (i.e., the data were not included in our data base), but actually were sampled. In two cases (Edgewater and Inland Steel) we overestimated the observed values and in the case of U.S. Steel/Gary our estimate was less than observed.

Recent estimates of the alewife standing crop in Lake Michigan placed the minimum total biomass at approximately $122\text{--}123 \times 10^6$ kg during 1974 and 1975 [24] and 56.5×10^6 [24] to 73.8×10^6 kg [25] in 1976. The assumption of a

total of 1.5×10^6 kg of alewife impinged at all water intakes in 1975 indicates that a maximum of 1.2% of the standing crop was lost due to impingement. The reported 54% decrease in biomass between 1975 and 1976 [24] is similar to the trend observed in impingement density at the Cook plant, i.e., a mean impingement density of 0.1319 alewife/1000 m³ in 1975 and 0.0912 alewife/1000 m³ in 1976 [19].

Table 7. Estimated total annual impingement of alewife at all water intakes within each statistical district on Lake Michigan (1975), assuming design flow operation at all intakes.

District	Total Flow (m ³)	Density (N/m ³)	Number	Kg
WM1	7.99×10^8	1.73×10^{-3}	1.38×10^6	5.87×10^4
WM2	0	0	0	0
WM3	0	0	0	0
WM4	2.39×10^9	7.30×10^{-4}	1.75×10^6	5.39×10^4
WM5	2.55×10^9	2.94×10^{-3}	7.48×10^6	1.90×10^5
WM6	2.51×10^9	1.03×10^{-3}	2.59×10^6	5.01×10^4
Illinois	6.46×10^9	6.44×10^{-3}	4.16×10^7	1.54×10^6
Indiana	8.10×10^9	4.88×10^{-4}	3.96×10^6	1.16×10^5
MM8	3.42×10^9	1.20×10^{-4}	4.10×10^5	1.22×10^4
MM7	7.03×10^8	1.20×10^{-4}	7.78×10^4	1.95×10^3
MM6	2.11×10^{10}	1.20×10^{-4}	2.53×10^6	7.50×10^4
MM5	0	0	0	0
MM4	3.32×10^7	1.16×10^{-6}	3.80×10^1	1.00×10^0
MM3	1.02×10^8	1.16×10^{-6}	1.18×10^2	4.00×10^0
MM2	9.95×10^6	1.16×10^{-6}	1.20×10^1	4.00×10^{-1}
MM1	9.08×10^7	1.16×10^{-6}	1.05×10^2	4.00×10^0
Total all intakes	4.83×10^{10}	-	6.18×10^7	2.10×10^6

Table 8. Comparison of estimated maximum annual impingement and entrainment values (1975) with observed annual values for Edgewater Power Plant (1975-1976), [1] Inland Steel (1976-1977), [22] and U.S. Steel/Gary (1977) [23] water intakes.

	Edgewater Power Plant		Inland Steel		U.S. Steel/Gary	
	ANL Est.	Obs.	ANL Est.	Obs.	ANL Est.	Obs.
Alewife	7.7×10^5	5.2×10^5	7.3×10^5	1.2×10^5	5.5×10^5	7.4×10^5
Rainbow smelt	2.4×10^4	1.8×10^3	1.6×10^3	5.6×10^3	1.2×10^3	6.4×10^4
Yellow perch	88	N/A	1.9×10^3	3.9×10^2	1.5×10^3	>860
Alewife eggs	2.5×10^6	3.0×10^7	7.7×10^9	1.8×10^8	5.9×10^9	N/A
larvae	4.4×10^5	1.8×10^4	6.3×10^7	2.3×10^7	4.7×10^7	N/A
Rainbow smelt eggs	5.7×10^4	0	9.9×10^6	3.0×10^7	7.5×10^6	N/A
larvae	1.0×10^5	3.9×10^5	2.8×10^6	3.4×10^6	2.1×10^6	N/A
Yellow perch eggs	0	N/A	3.0×10^4	N/A	2.3×10^4	N/A
larvae	3.0×10^3	N/A	3.4×10^4	N/A	2.6×10^4	N/A

Limnetics [1] reported an estimated total of 2.08×10^6 lbs (9.41×10^5 kg) of alewife impinged at 17 power plant intakes on Lake Michigan and

concluded that this biomass represents ~0.064% of the standing crop biomass, as reported by Edsall et al. [26]. Our estimate of alewife impingement at 16 plants (9.17×10^5 kg) is nearly identical to that reported by Limnetics, but more recent estimates [24] of the 1975 standing crop biomass indicate that the sampled power plants impinged a maximum of 0.75% of the total alewife biomass.

Rainbow Smelt Impingement - Sampled Intakes

In some ways, the impingement rates of smelt were dependent on time and location in a fashion similar to the impingement of alewife. A peak in smelt impingement occurred in April, presumably during the spawning period, but nearly equal peaks also occurred in July and October at the sampled intakes (Table 3). The numerical peak in October probably reflects the inshore aggregation of YOY smelt, as indicated by the relatively small increase in total weight impinged that month. The peak in July may have been related to hydrological conditions (e.g., upwelling) or some unknown interaction between smelt and other species, such as alewife. Although smelt impingement decreased during winter months, the decreases were not as pronounced as those observed for alewife.

The annual total smelt impingement at the sampled intakes was estimated to be 7.69×10^5 (9.77×10^3 kg) in 1975. Four plants on the western shore of Lake Michigan accounted for approximately 94% of the total observed smelt impingement (Table 4): i.e., 53% at Oak Creek (4.09×10^5), 23% at Point Beach (1.76×10^5), 10% at Port Washington (7.79×10^4), and 8% at Zion (5.80×10^4). In general, proportionately fewer smelt were impinged at intakes on the southern and eastern shores of the lakes (Figs. A.1.b-A.16.b). Maximum daily impingement densities were on the order of <5 smelt/1000 m³ at Pulliam, Point Beach, and Oak Creek; at other plants the maximum densities were generally <1 smelt/1000 m³.

Relatively little or no smelt impingement occurred during winter months at 6 of the sampled plants: Pulliam, Lakeside, Mitchell, Campbell, Palisades, and Big Rock. Evidence of major influxes of smelt during the spawning period was not as clear cut as that observed with alewife. Apparent spawning peaks in impingement were evident at Zion, Waukegan, Oak Creek, Stateline, Cook, and Campbell during March and April; and at Michigan City, Bailly, Lakeside, Pulliam, and Big Rock during April and May. Thus, no apparent locational effect was observed for the timing of the major spring impingement of smelt.

The mean weights of smelt impinged each month at each sampled intake are given in Table 9. The highest monthly mean weights (30-50 g) occurred either in winter or spring at most plants, and often coincided with the initiation of spring peaks in impingement. After spring maxima, mean weights tended to decrease with time and, beginning in July, YOY smelt apparently predominated the impingement, as evidenced by mean weight ranges between 3 and 10 g for 1 to 5 months in the late summer and fall. The monthly averages indicate a lakewide predominance of YOY smelt during August and September 1974 and 1975, and in October 1976. Although Zion and Cook data suggest increases in mean smelt weights between 1974 and 1976, lakewide means indicate a decrease in mean weight of smelt over this period. Conversely, the lakewide mean weights of impinged alewife may have increased slightly between 1974 and 1976 (Table 5). Considering the extensive sampling that is represented in these data, it

Table 9. Mean weights (g) of smelt impinged each month at 15 power plants on Lake Michigan, 1974-1976. Dashes indicate sampling but no smelt impinged.

Plant (ID)	Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Annual Mean Weights
Zion (1)	1974			31.1	32.4	27.3	24.8	24.0	15.6	12.7	47.9	43.1	52.2	28.9
	1975	38.4	62.9	50.3	32.9	-	-	11.2	19.5	21.0	32.1	37.7	58.2	50.6
Cook (2)	1975		18.5	9.0	20.5	16.7	11.1	10.2	4.3	5.0	1.5	7.2	10.7	12.6
	1976	10.6	23.6	14.4	28.4	8.6	9.2	12.2	19.6	12.9	5.2	13.3	13.0	14.1
Bailly (3)	1975												14.6	
	1976	21.6	3.9	30.9	42.3	11.9	7.2	3.4	2.8	-	-	-		22.2
Pulliam (5)	1975				37.6	25.9	-	20.5	-	-	37.7	-	40.0	37.4
	1976	-	-	-										
Kewaunee (6)	1975				18.1	17.1	18.0	20.0	20.1	20.0	25.4	24.7	28.6	24.7
	1976	28.3	34.0	37.9										
Point Beach (7)	1975			24.9	43.8	30.2	26.9	32.6	5.3	4.9	4.7	6.3	8.5	7.2
	1976	5.4	17.1											
Port Washington (8)	1975			26.8	33.4	26.8	21.4	6.4	5.4	7.9	21.5	24.5	24.8	11.5
	1976	22.8	25.5	-	-	28.6	11.9	-	-	-	12.5	14.3	-	18.2
Lakeside (9)	1975													
	1976	19.5	18.4											
Oak Creek (10)	1975			28.8	7.1	8.8	10.3	7.8	8.9	4.6	14.6	11.2	16.1	9.2
	1976	23.2	19.4											
Waukegan (11)	1975					17.5	10.2	4.7	6.9	8.0	13.2	20.0	47.9	22.0
	1976	27.0	34.3	22.6	26.8									
State Line (12)	1975			26.2	26.2	31.5	19.1	13.6	6.0	-	4.7	61.8	6.0	26.9
	1976	30.5	34.3	35.5										
Mitchell (13)	1975					28.7	15.3	5.7	6.5	9.1	7.3	4.8	8.4	12.0
	1976	22.7	33.7	23.8	40.7									
Campbell (14)	1974	-	-	-	26.7	19.5	34.9	-	-	-	-	7.5	28.3	20.0
	1975	28.3	-											
Palisades (15)	1974			-	35.3	-	-	-	-	-	-	-	-	35.3
	1975	-	-											
Big Rock (16)	1974			-	16.6	19.7	-	-	-	-	-	-	-	18.6
	1975	-	-	-										
Σ Mean Weights	1974	-	-	31.1	27.8	22.2	29.9	24.0	15.6	12.7	47.9	25.3	40.3	27.7
n Plants	1975	38.4	62.9	28.0	27.5	23.2	16.0	13.3	9.2	10.2	15.9	21.3	24.0	24.2
	1976	21.2	24.4	27.5	34.6	10.3	8.2	7.8	11.2	12.9	5.2	13.3	13.0	15.8

appears that mean weights of alewife and smelt vary as the inverse of each other.

Rainbow Smelt Impingement - Lakewide

Assuming design (capacity) flow at all water intakes on Lake Michigan, we estimated the maximum lakewide impingement of smelt to be 1.36×10^6 (1.86×10^4 kg)(Table 6). Accounting for the less than capacity flows at power plants, we conclude that at least 1×10^6 (1.4×10^4 kg) smelt were impinged at all intakes in 1975. Recent studies of smelt annual standing crop in Lake Michigan estimated the minimum smelt biomass to be 13.7×10^6 kg in 1975 and 11.1×10^6 kg in 1976 [27]. Assuming 1.4×10^4 kg to have been impinged at all intakes in 1975 and a stock of 13.7×10^6 kg, we conclude that a maximum of 0.10% of the biomass was lost due to impingement. Limnetics [1] estimated that 17 power plants impinged 9.17×10^3 kg of smelt in 1975, which amounted to 0.06% of the estimated 1974 standing crop biomass; our estimate of 9.77×10^3 kg for 16 power plants represents 0.07% of the estimated 1975 standing crop. Approximately 90% of the total annual impingement of smelt occurs at conventional power plants, despite the fact that only 43% of the total flow during the sampling period was used by these plants. The relatively low densities of smelt on the southern and eastern shores of Lake Michigan probably result in low numbers impinged despite large volumes of water withdrawn by the Ludington Pumped Storage Power Plant and municipal/industrial intakes in those regions.

Table 10. Estimated total annual impingement of rainbow smelt at all water intakes within each statistical district on Lake Michigan (1975), assuming design flow operation at all intakes.

District	Total Flow (m ³)	Density (N/m ³)	Number	Kg
WM1	7.99×10^8	2.18×10^{-5}	1.75×10^4	6.53×10^2
WM2	0	0	0	0
WM3	0	0	0	0
WM4	2.39×10^9	1.04×10^{-4}	2.49×10^5	2.22×10^3
WM5	2.55×10^9	9.31×10^{-5}	2.37×10^5	2.73×10^3
WM6	2.51×10^9	2.49×10^{-4}	6.24×10^5	5.73×10^3
Illinois	6.46×10^9	2.28×10^{-5}	1.48×10^5	6.23×10^3
Indiana	8.10×10^9	1.07×10^{-6}	8.69×10^3	1.67×10^2
MM8	3.42×10^9	2.86×10^{-6}	9.77×10^3	1.22×10^2
MM7	7.03×10^8	2.86×10^{-6}	1.08×10^3	1.90×10^1
MM6	2.11×10^{10}	2.86×10^{-6}	6.03×10^4	7.56×10^2
MM5	0	0	0	0
MM4	3.32×10^7	1.56×10^{-6}	5.20×10^1	1.00×10^0
MM3	1.02×10^8	1.56×10^{-6}	1.59×10^2	3.00×10^0
MM2	9.95×10^6	1.56×10^{-6}	1.55×10^1	3.00×10^{-1}
MM1	9.08×10^7	1.56×10^{-6}	1.42×10^2	3.00×10^0
Total all intakes	4.83×10^{10}	-	1.35×10^6	1.86×10^4

The estimated total annual impingement of smelt in each statistical district is given in Table 10. The mean annual densities of impinged smelt (calculated as the average of all daily observations at sampled intakes within a district) were highest in WM6 > WM4 > WM5 > Illinois > WM1, indicating the relatively high abundance of smelt on the western shore of the lake. The apparent spatial differences in smelt distribution negate the possibility of

establishing a clear relationship between volume of water withdrawn (flow) and impingement of smelt among statistical districts. For the same reasons given in the discussion of alewife data, the estimates of total smelt impingement in each statistical district should be interpreted with caution. In the case of districts with sampling results, the estimates are expected to be approximately correct. Table 8 presents a comparison of our estimates for three intakes that were sampled, but were not included in the observed data base. Two of the estimates (Inland Steel and U.S. Steel/Gary) were lower than reported by the industries, while that for the Edgewater plant was an order of magnitude higher than reported by Limnetics [1].

The reported standing crop biomass of smelt decreased ~19% between 1975 and 1976 [27]. A comparison of the mean annual impingement densities at the Cook plant between 1975 ($0.0029/1000 \text{ m}^3$) and 1976 ($0.0017/1000 \text{ m}^3$) indicates a decrease of ~40% in smelt abundance over this period.

Yellow Perch Impingement - Sampled Intakes

Numbers of yellow perch impinged at the 16 sampled intakes were greatest in the late fall-early winter (Table 3). Total biomass of impinged perch was highest in October, followed by May and November. A spawning-related peak of adults was impinged in May while larger numbers of other age classes were impinged in the late fall months. Lowest numbers and biomass of impinged perch occurred in the August-September and January-March periods of 1975.

The annual total perch impingement at the sampled intakes was estimated to be 1.39×10^5 ($3.11 \times 10^3 \text{ kg}$) in 1975. Eighty-five percent of the total biomass and 95% of the total number of impinged perch were taken by three power plants (Table 4); i.e., 85% of the total number at Pulliam (1.18×10^5); 9% at Cook (1.28×10^4); and 1% at Oak Creek (1.43×10^3). In general, few perch were impinged at most plants, except for those mentioned above. Maximum daily impingement densities were on the order of <3 perch/ 1000 m^3 at Pulliam between October-December and <1 perch/ 1000 m^3 at Cook between October-November. At all other plants, the maximum densities were <0.1 perch/ 1000 m^3 (Figs. A.1.c-A.16.c). Winter densities of impinged perch were not consistently low and indicate substantial inshore densities in winter in some areas of the lake; i.e., in the southern basin and isolated areas such as Green Bay (Pulliam) and Pigeon Lake (Campbell).

Yellow Perch Impingement - Lakewide

Assuming capacity flow at all water intakes on Lake Michigan, we estimated the maximum lakewide impingement of yellow perch to be 5.17×10^5 ($1.31 \times 10^4 \text{ kg}$) (Table 6). Accounting for the less than capacity flows at power plants, we conclude that at least 3.5×10^5 ($9.5 \times 10^3 \text{ kg}$) yellow perch were impinged in 1975. To date, no estimates are available for the standing crop biomass of yellow perch in Lake Michigan.

Approximately 60% of total annual impingement of yellow perch occurs at conventional power plants, while only 43% of the total flow during the sampling period was used by these plants. Based on the assumption that inshore yellow perch densities are similar between the Cook and Ludington areas, we estimate that the Ludington plant withdrew 1.88×10^5 yellow perch in 1975. This value represents approximately 36% of the estimated lakewide

total.

The estimated annual impingement of yellow perch in each statistical district is given in Table 11. The mean annual densities of impinged yellow perch (average of all daily observations at sampled intakes within a district) were highest in WM1 followed by MM8 and Indiana, indicating the relatively high abundance of perch in Green Bay and the southeastern areas of Lake Michigan. The values in Tables 6 and 11 should be interpreted with caution, since critical assumptions were made about the relative densities of yellow perch in unsampled districts. However, a comparison of estimated yellow perch impingement with observed values at intakes that were classified as unsampled (no data included in data base) shows very good agreements in districts where sampling data were included in the data base (Table 8).

Table 11. Estimated total annual impingement of yellow perch at all water intakes within each statistical district on Lake Michigan (1975), assuming design flow operation at all intakes.

District	Total Flow (m ³)	Density (N/m ³)	Number	Kg
WM1	7.99×10^8	3.52×10^{-4}	2.81×10^5	5.11×10^3
WM2	0	0	0	0
WM3	0	0	0	0
WM4	2.39×10^9	2.64×10^{-7}	6.31×10^2	1.01×10^2
WM5	2.55×10^9	3.34×10^{-7}	8.51×10^2	7.90×10^1
WM6	2.51×10^9	8.67×10^{-7}	2.17×10^3	1.61×10^2
Illinois	6.46×10^9	3.05×10^{-7}	1.97×10^3	2.32×10^2
Indiana	8.10×10^9	1.29×10^{-6}	1.04×10^4	6.64×10^2
MM8	3.42×10^9	8.91×10^{-6}	3.05×10^4	9.41×10^2
MM7	7.03×10^8	8.91×10^{-6}	1.44×10^3	4.00×10^1
MM6	2.11×10^{10}	8.91×10^{-6}	1.88×10^5	5.81×10^3
MM5	0	0	0	0
MM4	3.32×10^7	2.07×10^{-7}	7.00×10^0	1.00×10^0
MM3	1.02×10^8	2.07×10^{-7}	2.10×10^1	3.00×10^0
MM2	9.95×10^6	2.07×10^{-7}	2.00×10^0	2.00×10^{-1}
MM1	9.08×10^7	2.07×10^{-7}	1.90×10^1	2.00×10^0
Total all intakes	4.83×10^{10}	-	5.17×10^5	1.31×10^4

ENTRAINMENT ESTIMATES

Alewife Entrainment - Sampled Intakes

The major periods of entrainment were May through August for alewife eggs and June through September for alewife larvae (Table 12). Peaks in total entrainment at the sampled plants occurred in June for both alewife eggs and larvae. Each month, the numbers of entrained larvae were one to two orders of magnitude lower than the numbers of entrained eggs. No eggs were entrained during the period October through March. No larvae were entrained during the months January through April. An estimated total of 1.11×10^{10} eggs and 2.01×10^8 larvae were entrained at the 15 sampled intakes in 1975. The sampling periods probably were adequate to estimate the entrainment of alewife eggs, but may have been inadequate at some intakes to characterize the late summer-fall entrainment of alewife larvae. Therefore, the annual estimate of

entrained larvae is almost twice that observed.

Figures A.1.d-A.16.d show the time-dependent nature of alewife egg entrainment and indicate peak densities >100 eggs/m³ at Bailly, Waukegan, and Mitchell. Extremely low peak densities (<0.01 eggs/m³) were observed at the Campbell, Palisades, and Big Rock plants. Despite substantial impingements of alewife at Point Beach, Port Washington, Lakeside, and Oak Creek, the reported densities of entrained alewife eggs were uniformly low at these plants (<0.3 m³). This anomaly is difficult to explain in view of the fact that sampled plants to the north (e.g., Kewaunee) and south (e.g., Zion) of this group of plants showed substantially higher densities of entrained alewife eggs.

The initiation of alewife egg entrainment occurred 1-2 months after the initial large impingements of adults at all but one plant. At Pulliam, the initiation of alewife impingement lagged behind that at other plants (late May rather than April-May) and egg entrainment commenced almost immediately thereafter. The typical lag period between initial high impingement densities and egg entrainment indicates that early migrants (inshore occupants) are not completely gravid and become so while occupying warmer inshore waters in the spring. Peak larval densities (Figs. A.1.e-A.16.e) occurred 1-2 months after peak egg densities at most sampled intakes on the western shore of the lake (except Lakeside, Zion, and Waukegan) while on the southern and southeastern shores, the egg and larval peaks were much less separated in time. This apparent spatial difference may be the result of (1) accelerated growth rates of immature alewife in the warmer southern basin and/or (2) a net counterclockwise movement of inshore currents and ichthyoplankton in the southern basin of Lake Michigan. Peak densities of alewife larvae were >1 larvae/m³ at Cook and Bailly, and >0.1 /m³ at Zion, Waukegan, and Mitchell.

The estimated total numbers of alewife eggs and larvae entrained at each of the sampled intakes are given in Table 13. Intakes on the southern shore of Lake Michigan accounted for the majority of alewife eggs and larvae entrained by the sampled intakes. Bailly, Waukegan, Mitchell, Stateline, Cook, and Zion combined accounted for 96% of the total alewife eggs and 97% of the total alewife larvae entrained by the sampled intakes during 1975. Since the intakes on the western shore of the lake impinged the majority of adult alewife, it follows that the high entrainment densities on the southern shore may be the result of eggs and larvae being transported by counterclockwise inshore currents, and subsequently being entrained by intakes on the southern shore.

Alewife Entrainment - Lakewide

The maximum numbers of alewife eggs and larvae entrained by all water intakes on Lake Michigan were estimated to be 7.39×10^{10} and 1.31×10^9 , respectively, assuming capacity flow at all intakes (Table 14). Under these conditions, conventional power plants would account for approximately 54% of the total entrained alewife eggs, the Ludington plant would account for 8%, and municipal/industrial intakes for 38%. The relative percentage distribution by plant type for alewife larvae would be 28% by conventional power plants, 56% by Ludington, and 16% by the municipal/industrial plants. Since conventional power plants, as a group, typically withdraw ~50% of capacity flows on an annual basis, and most other intakes are assumed to operate near capacity flow, we estimate that at least 5×10^{10} alewife eggs and 1×10^9

Table 12. Estimated total numbers of alewife, rainbow smelt, and yellow perch eggs and larvae entrained each month during the sampling periods at all 15 sampled power plants; estimated annual totals by extrapolation to full year for each plant (1975).

	Total Flow (m ³)	Alewife		Smelt		Perch	
		Eggs	Larvae	Eggs	Larvae	Eggs	Larvae
January	1.63 x 10 ⁸	0	0	0	6.00 x 10 ⁰	0	0
February	1.83 x 10 ⁸	0	0	0	5.42 x 10 ⁴	0	0
March	2.30 x 10 ⁸	0	0	1.01 x 10 ⁵	4.48 x 10 ⁴	1.24 x 10 ⁴	0
April	5.54 x 10 ⁸	8.24 x 10 ⁵	0	5.80 x 10 ⁷	3.72 x 10 ⁴	0	0
May	9.07 x 10 ⁸	2.30 x 10 ⁸	3.63 x 10 ⁵	2.83 x 10 ⁷	5.44 x 10 ⁶	1.01 x 10 ⁶	4.49 x 10 ⁵
June	9.96 x 10 ⁸	6.17 x 10 ⁹	6.28 x 10 ⁷	3.41 x 10 ⁶	6.55 x 10 ⁵	5.35 x 10 ⁶	1.22 x 10 ⁵
July	1.05 x 10 ⁹	3.88 x 10 ⁹	5.82 x 10 ⁷	0	2.37 x 10 ⁶	1.26 x 10 ⁴	2.96 x 10 ⁴
August	1.06 x 10 ⁹	1.77 x 10 ⁸	8.22 x 10 ⁶	0	4.53 x 10 ⁶	0	0
September	7.73 x 10 ⁸	3.41 x 10 ⁵	3.56 x 10 ⁶	0	3.72 x 10 ⁶	0	0
October	6.30 x 10 ⁸	0	1.13 x 10 ⁵	0	2.81 x 10 ⁶	0	0
November	2.67 x 10 ⁸	0	8.03 x 10 ²	0	9.40 x 10 ⁵	0	0
December	2.19 x 10 ⁸	0	1.30 x 10 ¹	0	4.25 x 10 ⁴	0	0
Total observed	7.04 x 10 ⁹	1.05 x 10 ¹⁰	1.33 x 10 ⁸	8.98 x 10 ⁷	2.06 x 10 ⁷	6.38 x 10 ⁶	6.01 x 10 ⁵
Estimated annual total	-	1.11 x 10 ¹⁰	2.01 x 10 ⁸	3.10 x 10 ⁸	2.71 x 10 ⁷	6.77 x 10 ⁶	6.12 x 10 ⁵

Table 13. Estimated total numbers of alewife, rainbow smelt, and yellow perch eggs and larvae entrained during the sampling periods at each of the 15 sampled power plants; estimated annual totals by extrapolation to full year for each plant (1975).

	Total Flow (m ³)	Alewife		Smelt		Perch	
		Eggs	Larvae	Eggs	Larvae	Eggs	Larvae
Zion	5.52 x 10 ⁸	4.73 x 10 ⁸	4.39 x 10 ⁶	4.47 x 10 ⁷	3.13 x 10 ⁶	N/A	N/A
Cook	1.30 x 10 ⁹	6.21 x 10 ⁸	6.51 x 10 ⁷	7.86 x 10 ⁶	2.91 x 10 ⁵	4.05 x 10 ⁶	6.37 x 10 ⁴
Baillly	6.16 x 10 ⁸	3.86 x 10 ⁹	3.80 x 10 ⁷	4.14 x 10 ⁶	2.87 x 10 ⁵	1.24 x 10 ⁴	1.42 x 10 ⁴
Michigan City	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Pulliam	1.52 x 10 ⁸	2.93 x 10 ⁸	4.84 x 10 ⁴	6.87 x 10 ⁵	2.52 x 10 ⁴	2.32 x 10 ⁶	5.17 x 10 ⁵
Kewaunee	5.33 x 10 ⁸	4.71 x 10 ⁷	6.03 x 10 ⁵	9.85 x 10 ⁵	9.45 x 10 ⁶	N/A	N/A
Point Beach	8.08 x 10 ⁸	4.11 x 10 ⁶	3.31 x 10 ⁵	0	1.21 x 10 ⁶	N/A	N/A
Port Washington	3.42 x 10 ⁸	2.70 x 10 ⁶	2.95 x 10 ⁵	1.16 x 10 ⁵	2.99 x 10 ⁵	0	5.64 x 10 ³
Lakeside	1.41 x 10 ⁸	3.07 x 10 ⁶	6.29 x 10 ⁵	0	0	N/A	N/A
Oak Creek	8.93 x 10 ⁸	6.14 x 10 ⁶	1.59 x 10 ⁶	5.96 x 10 ⁴	4.41 x 10 ⁶	N/A	N/A
Waukegan	4.08 x 10 ⁸	2.93 x 10 ⁹	1.18 x 10 ⁷	2.73 x 10 ⁷	1.37 x 10 ⁵	N/A	N/A
Stateline	5.26 x 10 ⁸	7.12 x 10 ⁸	2.97 x 10 ⁶	3.61 x 10 ⁶	8.07 x 10 ⁴	N/A	N/A
Mitchell	2.24 x 10 ⁸	1.51 x 10 ⁹	7.41 x 10 ⁶	2.32 x 10 ⁵	1.34 x 10 ⁶	N/A	N/A
Campbell	3.35 x 10 ⁸	6.48 x 10 ⁴	2.25 x 10 ³	1.24 x 10 ²	1.49 x 10 ³	0	0
Palisades	9.94 x 10 ⁷	0	7.00 x 10 ⁰	1.40 x 10 ¹	1.30 x 10 ¹	0	0
Big Rock	1.07 x 10 ⁸	0	1.05 x 10 ¹	5.47 x 10 ²	1.43 x 10 ²	0	0
Total observed	7.04 x 10 ⁹	1.05 x 10 ¹⁰	1.33 x 10 ⁸	8.98 x 10 ⁷	2.06 x 10 ⁷	6.38 x 10 ⁶	6.01 x 10 ⁵
Estimated annual total	-	1.11 x 10 ¹⁰	2.01 x 10 ⁸	3.10 x 10 ⁸	2.71 x 10 ⁷	6.77 x 10 ⁶	6.12 x 10 ⁵

alewife larvae were entrained by all water intakes on Lake Michigan in 1975. Table 15 shows the estimated maximum numbers of alewife eggs and larvae entrained in 1975 by statistical district. From these estimates, it is clear that the majority of alewife eggs and larvae are entrained in Illinois, Indiana, and MM6, the districts with the greatest water withdrawal. Our estimates for district MM6 (primarily the Ludington Pump Storage Plant) are based on the assumption that inshore densities of alewife eggs and larvae in that district are equal to those in district MM8, since no intakes were sampled in MM6. Our estimation procedure seems to yield reasonable estimates for "unsampled" intakes (not in our data base but observations available) in districts where sampling was performed (Table 8).

The total number of alewife larvae entrained at the sampled intakes (Table 12) represents approximately 1.8% of the total number of eggs entrained by those intakes indicating a 98% mortality between egg and larval stages of development. Extrapolation of these values to all intakes on Lake Michigan (Table 14) also indicates a 98% mortality between egg and larval stages. For a number of reasons, these estimates may not reflect actual mortality rates between the egg and larval stages of alewife in Lake Michigan. This crude approach assumes that (1) power plant intakes "sample" eggs and larvae at equal efficiencies which may not be true; and (2) the sampled intakes provided unbiased estimates of actual egg and larval densities in Lake Michigan waters. Many studies of fish population dynamics have shown that clupeid species tend to undergo high mortality rates during the first year of life, and it is usually assumed that mortality from egg to adult stages exceeds 99%.

Rainbow Smelt Entrainment - Sampled Intakes

The major periods of entrainment were March through June for smelt eggs and May through November for smelt larvae (Table 12). Peaks in total entrainment at the sampled plants occurred in April for eggs and in May and August for larvae. No smelt eggs were entrained between July and February but at least 3×10^4 smelt larvae were reported each month except for January. The monthly totals for smelt larvae in Table 12 show a bimodal distribution with time (i.e., peaks in May and August) and may indicate either (1) altered spatial distribution of larvae over time, or (2) the existence of two or more separate spawning times lakewide.

An estimated total of 3.10×10^8 smelt eggs and 2.71×10^7 smelt larvae were entrained at the 15 sampled intakes in 1975. The sampling periods were not initiated soon enough at some of the southern basin intakes to adequately characterize egg entrainment; therefore, the annual estimate of entrained eggs is approximately three times the observed value. Larval entrainment was adequately characterized during the sampling periods at most of the sampled intakes.

Figures A.1.f-A.16.f show the time-dependent nature of smelt egg entrainment and indicate peak densities >1 egg/m³ at the Zion and Waukegan plants in April. Numerous plants had peak densities >0.1 egg/m³ (e.g., Cook, Bailly, Pulliam, Kewaunee, and Stateline). Extremely low egg densities and total egg entrainment were observed at Point Beach and Campbell, despite substantial impingements of smelt at these plants (Table 4).

Smelt egg entrainment commenced about the same time as smelt impingement

Table 14. Estimated total numbers of alewife, smelt, and yellow perch eggs and larvae entrained at sampled power plants, unsampled power plants, and municipal/industrial intakes on Lake Michigan, assuming design flow operation (1975).

	Total Flow (m ³)	Alewife		Smelt		Perch	
		Eggs	Larvae	Eggs	Larvae	Eggs	Larvae
15 sampled power plants	1.97×10^{10}	3.66×10^{10}	3.40×10^8	4.06×10^8	6.37×10^7	1.67×10^7	2.54×10^6
Unsampled power plants	9.67×10^8	3.15×10^9	2.57×10^7	5.10×10^6	1.54×10^6	1.20×10^4	1.67×10^4
Total conventional plants	2.07×10^{10}	3.97×10^{10}	3.66×10^8	4.11×10^8	6.52×10^7	1.67×10^7	2.55×10^6
Ludington P.S. plant	2.11×10^{10}	5.85×10^9	7.30×10^8	5.99×10^7	2.33×10^6	3.08×10^7	5.28×10^5
Total all power plants	4.18×10^{10}	4.56×10^{10}	1.10×10^9	4.71×10^8	6.75×10^7	4.75×10^7	3.08×10^6
Total municipal/industrial	6.51×10^9	2.83×10^{10}	2.14×10^8	1.44×10^8	1.53×10^7	6.49×10^5	1.81×10^5
Total all intakes	4.83×10^{10}	7.39×10^{10}	1.31×10^9	6.15×10^8	8.28×10^7	4.81×10^7	3.26×10^6

Table 15. Estimated total annual entrainment of alewife eggs and larvae at all water intakes within each statistical district on Lake Michigan (1975), assuming design flow operation at all intakes.

District	Total Flow (m ³)	Eggs		Larvae	
		Density (N/m ³)	Number	Density (N/m ³)	Number
WM1	7.99×10^8	1.44×10^0	1.15×10^9	1.99×10^{-4}	1.59×10^5
WM2	0	0	0	0	0
WM3	0	0	0	0	0
WM4	2.39×10^9	4.85×10^{-2}	1.16×10^8	7.80×10^{-4}	1.87×10^6
WM5	2.55×10^9	9.61×10^{-3}	2.45×10^7	1.66×10^{-3}	4.24×10^6
WM6	2.51×10^9	7.01×10^{-3}	1.76×10^7	1.66×10^{-3}	4.15×10^6
Illinois	6.46×10^9	3.68×10^0	2.38×10^{10}	1.66×10^{-2}	1.07×10^8
Indiana	8.10×10^9	5.18×10^0	4.20×10^{10}	4.19×10^{-2}	3.40×10^8
MM3	3.42×10^9	2.77×10^{-1}	9.47×10^8	3.46×10^{-2}	1.18×10^8
MM7	7.03×10^8	2.77×10^{-1}	2.96×10^7	3.46×10^{-2}	3.68×10^6
MM6	2.11×10^{10}	2.77×10^{-1}	5.85×10^9	3.46×10^{-2}	7.30×10^8
MM5	0	0	0	0	0
MM4	3.32×10^7	0	0	9.47×10^{-8}	3.20×10^0
MM3	1.02×10^8	0	0	9.47×10^{-8}	9.60×10^0
MM2	9.95×10^6	0	0	9.47×10^{-8}	9.00×10^{-1}
MM1	9.08×10^7	0	0	9.47×10^{-8}	9.00×10^0
Total all intakes	4.83×10^{10}	-	7.38×10^{10}	-	1.31×10^9

increased in the spring at some plants (Cook, Bailly, Pulliam, Waukegan, Stateline, and Big Rock), but at other plants it was delayed at least a month relative to the increase in impingement (Kewaunee, Port Washington, and Oak Creek). Since a number of plants impinged smelt over the winter months and the normal hatching time for smelt eggs ranges from 3-5 weeks, it is difficult to determine if a lag period exists between inshore migrations and spawning. Although egg entrainments typically were confined to less than three months at any plant, larval entrainment (Figs. A.1.g-A.16.g) was spread out over 6-9 months at some plants (e.g., Kewaunee and Oak Creek). This pattern must result from the transport of eggs and larvae spawned at remote locations and from the slow development of smelt larvae into motile juveniles that are too large to be entrained. Thus, smelt young are vulnerable to entrainment for longer periods of time and by more water intakes than are alewife young. Peak densities of larvae were $>0.1/m^3$ at Zion, Kewaunee, and Mitchell, and $>0.01/m^3$ at Bailly, Point Beach, Port Washington, and Oak Creek. Very low densities of smelt larvae ($<0.0001/m^3$) were entrained at Lakeside, Campbell, Palisades, and Big Rock. Smelt larval densities were equal to or greater than egg densities at Kewaunee, Point Beach, Port Washington, Oak Creek, and Mitchell, another indication of long-range transport and extended vulnerability of planktonic smelt to entrainment.

The estimated total numbers of smelt eggs and larvae entrained at each of the sampled intakes are given in Table 13. Eighty percent of the smelt eggs entrained by sampled intakes were taken at the Zion and Waukegan plants, while 98% were entrained by five plants in the southern basin (Zion, Cook, Bailly, Waukegan, and Stateline). However, entrainment of smelt larvae was not concentrated in the southern basin, but was nearly equal between northern and southern plants taken as groups. In the north, Kewaunee and Point Beach accounted for 52% of the lakewide total (observed) and in the south, Zion, Oak Creek, Mitchell, Waukegan, and Port Washington accounted for 45% of the total entrained smelt larvae. This difference between egg and larval distribution indicates that substantial smelt spawning may be occurring on the northwestern shore of Lake Michigan, as well as in the southern basin.

Smelt Entrainment - Lakewide

The maximum numbers of smelt eggs and larvae entrained by all water intakes on Lake Michigan were estimated to be 6.15×10^8 and 8.28×10^7 , respectively, assuming capacity flows at all water intakes (Table 14). Under these conditions conventional power plants would account for 67% of the total entrained smelt eggs, the Ludington plant would account for 10%, and the municipal/industrial intakes would entrain 23% of the total eggs. The relative distribution of entrained smelt larvae by plant type would be 79% by conventional power plants, 3% by the Ludington plant, and 18% by municipal/industrial intakes. Under normal flow assumptions, we estimate that at least 5×10^8 smelt eggs and 5×10^7 smelt larvae were entrained by all water intakes on Lake Michigan in 1975. The estimated maximum numbers of smelt eggs and larvae entrained in 1975 within each statistical district are given in Table 16. These estimates indicate that the majority of smelt eggs are entrained in Illinois while smelt larvae are heavily entrained in Illinois, Indiana, WM4, and WM6. The accuracy of these estimates is indicated by the good agreement between our estimates for "unsampled" intakes and observed data at those intakes for smelt eggs and larvae (Table 8).

Table 16. Estimated total annual entrainment of rainbow smelt eggs and larvae at all water intakes within each statistical district on Lake Michigan (1975), assuming design flow operation at all intakes.

District	Total Flow (m ³)	Eggs		Larvae	
		Density (N/m ³)	Number	Density (N/m ³)	Number
WM1	7.99 x 10 ⁸	5.14 x 10 ⁻³	4.10 x 10 ⁶	1.37 x 10 ⁻⁴	1.09 x 10 ⁵
WM2	0	5.14 x 10 ⁻³	0	1.37 x 10 ⁻⁴	0
WM3	0	2.52 x 10 ⁻³	0	1.03 x 10 ⁻²	0
WM4	2.39 x 10 ⁹	2.52 x 10 ⁻³	6.03 x 10 ⁶	1.03 x 10 ⁻²	2.46 x 10 ⁷
WM5	2.55 x 10 ⁹	2.16 x 10 ⁻⁴	5.51 x 10 ⁵	3.99 x 10 ⁻⁴	1.02 x 10 ⁶
WM6	2.51 x 10 ⁹	7.57 x 10 ⁻⁵	1.90 x 10 ⁵	4.45 x 10 ⁻³	1.11 x 10 ⁷
Illinois	6.46 x 10 ⁹	7.43 x 10 ⁻²	4.80 x 10 ⁸	4.38 x 10 ⁻³	2.83 x 10 ⁷
Indiana	8.10 x 10 ⁹	6.61 x 10 ⁻³	5.36 x 10 ⁷	1.84 x 10 ⁻³	1.49 x 10 ⁷
MM8	3.42 x 10 ⁹	2.84 x 10 ⁻³	9.70 x 10 ⁶	1.10 x 10 ⁻⁴	3.77 x 10 ⁵
MM7	7.03 x 10 ⁸	2.84 x 10 ⁻³	3.02 x 10 ⁵	1.10 x 10 ⁻⁴	1.44 x 10 ⁴
MM6	2.11 x 10 ¹⁰	2.84 x 10 ⁻³	5.99 x 10 ⁷	1.10 x 10 ⁻⁴	2.33 x 10 ⁶
MM5	0	0	0	0	0
MM4	3.32 x 10 ⁷	4.94 x 10 ⁻⁶	1.64 x 10 ²	1.29 x 10 ⁻⁶	4.27 x 10 ¹
MM3	1.02 x 10 ⁸	4.94 x 10 ⁻⁶	5.03 x 10 ²	1.29 x 10 ⁻⁶	1.31 x 10 ²
MM2	9.95 x 10 ⁶	4.94 x 10 ⁻⁶	4.92 x 10 ¹	1.29 x 10 ⁻⁶	1.28 x 10 ¹
MM1	9.08 x 10 ⁷	4.94 x 10 ⁻⁶	4.49 x 10 ²	1.29 x 10 ⁻⁶	1.17 x 10 ²
Total all intakes	4.83 x 10 ¹⁰	-	6.14 x 10 ⁸	-	8.28 x 10 ⁷

The total number of smelt larvae entrained at the sampled intakes (Table 12) represents approximately 9% of the total number of smelt eggs entrained at these intakes and indicates a 91% mortality between eggs and larvae. From Table 14, the lakewide estimates indicate an 87% mortality between egg and larval stages of development. These estimates of mortality between egg and larval stages of smelt in Lake Michigan should be used with caution, for the same reason given in the discussion of alewife egg-larvae mortality.

Yellow Perch Entrainment - Sampled Intakes

Yellow perch eggs were entrained between March and July, with peak entrainment occurring in May and June. Yellow perch larvae were entrained between May and July, with major entrainment in May and June (Table 12). No eggs or larvae were entrained between August and February. An estimated total of 6.77×10^6 eggs and 6.12×10^5 larvae were entrained at the 15 sampled intakes in 1975 (Table 13). Two power plants (Pulliam and Cook) accounted for 99.8% of the total eggs and 96.6% of the total larvae entrained by the sampled intakes. However, it must be noted that a large fraction of the plants that were sampled did not identify (report) perch eggs and larvae; therefore, the actual distribution of immature perch may be somewhat different than that reflected by Table 13.

Figures A.2.h-A.16.h and A.2.i-A.16.i show the entrainment rates (densities) of yellow perch eggs and larvae, respectively, at each sampled plant (only those plants that identified perch eggs or larvae were included). Of the three plants that reported yellow perch eggs, Pulliam recorded the highest densities (~ 0.3 eggs/m³), followed by Cook (~ 0.04 eggs/m³), and Bailly (~ 0.001 eggs/m³). Although every sampled plant impinged some yellow perch (Table 4), Pulliam and Cook impinged $\sim 95\%$ of the observed

totals. This indicates that minor entrainment of eggs and larvae probably occurred at the majority of plants.

The earliest yellow perch egg entrainment was recorded at the Bailly plant in March, while at Pulliam and Cook egg entrainment started in April to May and peaked in May to June. Yellow perch were impinged at variable rates prior to the egg entrainment and no clear spawning influx was evident. Larval entrainment began >3 weeks after the initial appearance of eggs at each of the three plants that recorded both eggs and larvae. Maximum densities of larvae were observed at Pulliam (~ 0.04 larvae/m³). The yellow perch larvae entrained by Port Washington may have been transported from the northwestern shore by lake currents.

Yellow Perch Entrainment - Lakewide

The maximum numbers of yellow perch eggs and larvae entrained by all water intakes on Lake Michigan were estimated to be 4.81×10^7 and 3.26×10^6 , respectively, assuming capacity flows at all intakes (Table 14). Under these conditions, conventional power plants would account for $\sim 35\%$ of the total entrained perch eggs, the Ludington plant would account for 64% of the total, and municipal/industrial intakes for $\sim 1\%$ of the total. The relative distribution of yellow perch larvae by plant type would be: 78% by conventional power plants, 16% by Ludington, and 6% by municipal/industrial intakes. Under normal flow assumptions, we estimate that $\sim 4 \times 10^7$ yellow perch eggs and 1×10^6 yellow perch larvae were entrained by all water intakes on Lake Michigan in 1975.

The estimated maximum numbers of yellow perch eggs and larvae entrained within each statistical district in 1975 are given in Table 17. These estimates indicate that the majority of yellow perch eggs and larvae were entrained in MM6, MM1, and MM8. Unfortunately, no observations were available for

Table 17. Estimated total annual entrainment of yellow perch eggs and larvae at all water intakes within each statistical district on Lake Michigan (1975), assuming design flow operation at all intakes.

District	Total Flow (m ³)	Eggs		Larvae	
		Density (N/m ³)	Number	Density (N/m ³)	Number
WM1	7.99×10^8	1.51×10^{-2}	1.21×10^7	3.04×10^{-3}	2.43×10^6
WM2	0	1.51×10^{-2}	0	3.04×10^{-3}	0
WM3	0	N/A	0	N/A	0
WM4	2.39×10^9	N/A	N/A	N/A	N/A
WM5	2.55×10^9	0	0	1.14×10^{-5}	2.90×10^4
WM6	2.51×10^9	N/A	N/A	N/A	N/A
Illinois	6.46×10^9	N/A	N/A	N/A	N/A
Indiana	8.10×10^9	2.01×10^{-5}	1.63×10^5	2.29×10^{-5}	1.86×10^5
MM8	3.42×10^9	1.46×10^{-3}	4.98×10^6	2.51×10^{-5}	8.56×10^4
MM7	7.03×10^8	1.46×10^{-3}	1.55×10^5	2.51×10^{-5}	2.66×10^3
MM6	2.11×10^{10}	1.46×10^{-3}	3.08×10^7	2.51×10^{-5}	5.28×10^5
MM5	0	0	0	0	0
MM4	3.32×10^7	0	0	0	0
MM3	1.02×10^8	0	0	0	0
MM2	9.95×10^6	0	0	0	0
MM1	9.08×10^7	0	0	0	0
Total all intakes	4.83×10^{10}	-	4.81×10^7	-	3.26×10^6

intakes not included in our data base; thus, no comparisons can be made between our estimates for "unsampled" intakes and actual observations.

The total number of yellow perch larvae entrained at the sampled intakes (Table 13) represents ~9% of the total number of entrained perch eggs and indicates a 91% mortality. From Table 14 a lakewide estimate indicates a 93% mortality between egg and larval stages of development. These estimates may not reflect actual mortality rates between perch egg and larval stages in Lake Michigan.

FACTORS AFFECTING IMPINGEMENT AND ENTRAINMENT

Effects of Intake Type

As of 1975, three types of water intakes were used by the electrical utility industry on Lake Michigan: canals (CNL), offshore open bays (OOB), and porous dikes (PD). Six of the 16 sampled power plant intakes are canals, four are offshore open bays, and six are porous dikes (Table 1). A number of factors, besides intake type, probably affected the observed impingement and entrainment densities at the sampled intakes: e.g., flow rate, location, and most important, the local inshore densities of each species/lifestage. Inshore densities of most species are highly variable in space and no data were available that would allow corrections of observed intake densities for spatial differences in fish abundance (i.e., impingement/entrainment densities at each sampled intake could not be normalized for local abundances). Despite these problems, we made statistical comparisons of the lakewide mean densities between the three types of water intakes. Intakes of each type were sampled in each basin and on each shore of Lake Michigan.

Alewife

The results of statistical comparisons between lakewide impingement densities at each type of intake are presented in Table 18. Alewife impingement densities (rates) tended to be significantly higher at canal intakes in summer, fall, and winter, and significantly higher at offshore open bay intakes in spring. A similar trend was found when all sampled intakes were grouped into "offshore" or "onshore" locations: i.e., onshore intakes impinged significantly higher numbers of alewife in summer and winter, while offshore intakes impinged more alewife in spring. Figure 2 shows the annual mean densities of alewife at each of the sampled intakes, grouped by type. It is apparent from this arrangement of the data that (1) the Zion plant experienced an inordinately high density of impinged alewife compared to other OOB intakes, and (2) excluding Zion from the OOB group would result in canals having the highest annual mean density. This indicates that the Zion site was relatively high in alewife abundance and that the OOB intake design (without the behavioral barrier-net) is not very protective of alewife. Figure 2 also shows that the intakes sited on the western and southern shores of Lake Michigan experience the highest annual impingement densities of alewife, regardless of the intake type.

A statistical comparison of lakewide entrainment densities of alewife eggs and larvae between intake types is presented in Table 19. Canal and porous dike intakes entrained statistically equal mean densities of alewife

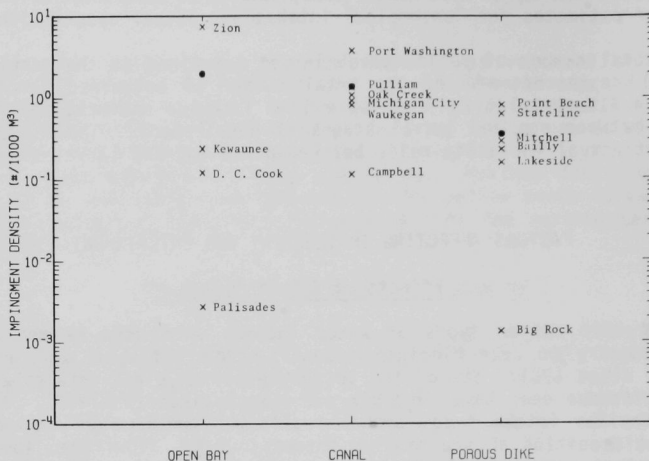


Fig. 2. Mean annual densities of impinged alewife at each sampled intake (1975). Circles represent means for each intake type.

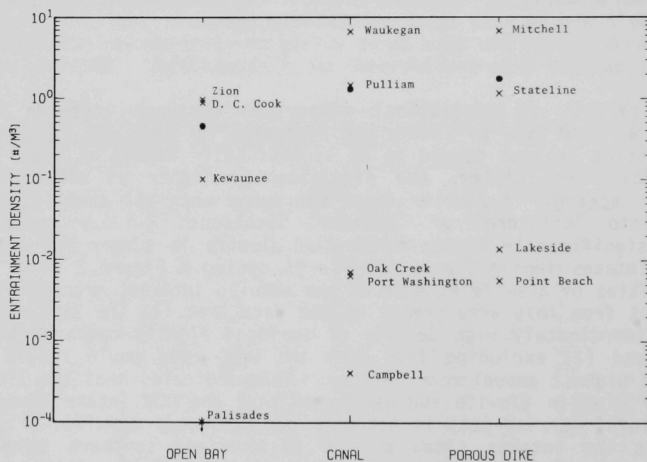


Fig. 3. Mean annual densities of entrained alewife eggs at each sampled intake (1975). Circles represent means for each intake type.

eggs while the densities entrained by OOB intakes were significantly lower. Onshore intakes entrained significantly higher densities of alewife eggs than those entrained by offshore intakes. The exact opposite relationship was found for alewife larvae: i.e., OOB > CNL = PD and offshore > onshore. Figures 3 and 4 show the mean annual densities of alewife eggs and larvae, respectively, entrained by each sampled intake. The apparent high abundance of adult alewife on the western shore of Lake Michigan (Fig. 2) is reversed for the entrainment of eggs and larvae: i.e., canal intakes on the western shore (Oak Creek and Port Washington) entrained relatively few alewife eggs and larvae compared to intakes sited on the southern shores.

Table 18. Statistical comparisons between lakewide monthly mean impingement densities of alewife, smelt, and yellow perch for intake locations and types.^a

Month	Alewife						Smelt						Yellow Perch					
	Intake Location ^b		Intake Type ^c				Intake Location		Intake Type				Intake Location		Intake Type			
	Onshore	Offshore	OOB	CNL	PD		Onshore	Offshore	OOB	CNL	PD		Onshore	Offshore	OOB	CNL	PD	
January	A	A	AB	A	B	B	A	A	B	A	A	A	B	B	B	A	B	B
February	A	B	B	A	B	B	A	A	A	B	A	A	B	B	B	A	B	B
March	B	A	A	B	B	B	A	A	A	B	B	A	A	B	A	B	A	B
April	A	A	A	B	A	A	B	B	A	B	A	B	A	B	B	A	B	B
May	B	A	A	B	B	B	A	B	A	B	A	B	A	B	B	A	B	B
June	A	B	B	A	B	A	B	B	A	B	A	B	A	B	B	A	B	B
July	A	B	C	A	B	A	B	B	A	B	A	B	B	B	B	A	B	B
August	A	B	B	A	B	A	B	B	A	B	A	B	B	B	B	A	B	B
September	A	A	B	A	B	B	A	B	B	B	A	A	B	B	B	A	B	B
October	A	A	B	A	A	B	A	A	A	A	A	A	B	B	B	A	B	B
November	A	A	A	A	A	B	A	A	A	A	A	A	B	B	B	A	B	B
December	A	B	B	AB	A	B	A	A	A	B	A	A	B	B	B	A	B	B

^a OOB = offshore open bay; CNL = canal; PD = porous dike.

^b t-test A > B > C.

^c AOY $\alpha = 0.05$.

Table 19. Statistical comparisons between lakewide annual mean entrainment densities of each species-life stage for intake locations and types.^a

Species/Stage	Intake Location ^b		Intake Type ^c		
	Onshore	Offshore	OOB	CNL	PD
Alewife eggs	A	B	B	A	A
Alewife larvae	B	A	A	B	B
Rainbow smelt eggs	B	A	A	B	C
Rainbow smelt larvae	B	A	A	B	B
Yellow perch eggs	A	A	A	A	-
Yellow perch larvae	A	B	B	A	-

^a OOB = offshore open bay; CNL = canal; PD = porous dike.

^b t-test A > B > C.

^c AOY $\alpha = 0.05$.

A different approach to the same question regarding intake-type effects was applied whereby regional and temporal differences in abundance were eliminated by comparing monthly mean densities of a species/lifestage between

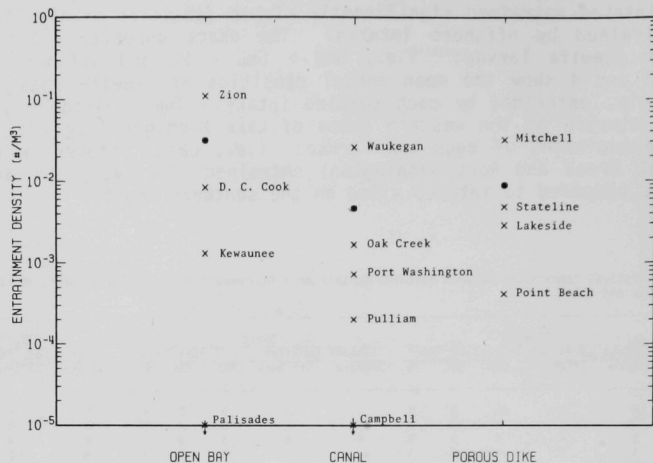


Fig. 4. Mean annual densities of entrained alewife larvae at each sampled intake (1975). Circles represent means for each intake type.

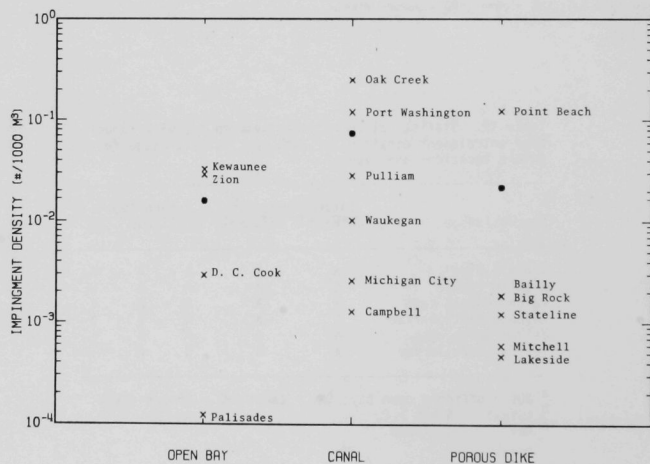


Fig. 5. Mean annual densities of impinged smelt at each sampled intake (1975). Circles represent means for each intake type.

"adjacent" intakes of different designs. Tables 20, 21, and 22 present the statistical comparisons between alewife densities at "adjacent" intakes that were sampled at the same time. Alewife impingement densities (Table 20) were significantly higher in most months at four canal intakes (Waukegan, Port Washington, Oak Creek, and Michigan City) that were compared with "adjacent" intakes of other types. The very high alewife impingement at Zion through May 1975 is reflected in the Zion-Waukegan comparison, but the significantly higher densities at Waukegan from June through December indicate the relative efficiency of canal intakes for entrapping alewife.

Two of the comparisons in Table 20 are between similar "adjacent" intakes (2 canals and 2 porous dikes) and they clearly show that very similar intakes in the same region of the lake impinge alewife at significantly different rates at least eight months of the year: i.e., Port Washington > Oak Creek for 8 out of 12 months, Stateline > Mitchell for 4 months during alewife spawning runs, but Mitchell > Stateline during 4 months in fall and winter. No explanation is apparent for the differences between the densities of alewife impinged at the two canal intakes (Port Washington vs. Oak Creek) other than the distance of ~37 miles between them. The two porous dikes (Mitchell vs. Stateline) are separated by ~20 miles and are slightly different in that the Mitchell intake extends further offshore and utilizes an electric fish screen in the intake forebay.

Tables 21 and 22 present the intake-pair comparisons for entrainment densities of alewife eggs and larvae, respectively. Only one canal and one OOB intake entrained consistently higher densities of eggs (i.e., Waukegan vs. Zion and Kewaunee vs. Point Beach). All other comparisons were equivocal except that Mitchell's porous dike intake rather consistently entrained more alewife eggs/unit volume than the porous dike at Stateline. Entrainment densities of alewife larvae were higher at canal intakes in late summer, while densities entrained by porous dikes may have been higher in early summer. The higher densities of larvae at Mitchell as compared to those at Stateline may reflect the apparent lakewide difference between offshore and onshore intakes (Table 19).

In conclusion, the results of lakewide and paired intake comparisons indicate that, with the exception of the Zion intake operated without a protective net, canal and onshore PD intakes impinge more alewife per unit volume than OOB or OPD intakes. Onshore intakes, and offshore porous dikes apparently entrain more alewife eggs/unit volume, while offshore open bays entrain higher densities of alewife larvae. These indications may reflect the following: (1) spawning alewife tend to be anadromous and may seek harbors, rivers, and canals despite reverse flow characteristics of intake canals; (2) alewife eggs are demersal (negatively buoyant) but remain semi-planktonic and may be equally vulnerable to onshore and offshore intake types; and (3) alewife larvae are semi-planktonic and may concentrate near the bottom in offshore areas where open bay intakes are located. The comparisons between similar "adjacent" intakes indicate the degree of spatial variability in abundances of adult and young alewife, and demonstrate the potential errors associated with comparisons of this type.

Rainbow Smelt

Lakewide annual impingement densities of rainbow smelt (Table 18) indi-

Table 20. Statistical comparisons of the monthly mean densities ($N/1000^3$) of impinged alewife between dissimilar and similar intakes that are "adjacent" to one another. Underlined densities are significantly higher ($\alpha = 0.05$).

	January	February	March	April	May	June	July	August	September	October	November	December
Kewaunee vs. Point Beach												
04/01/75-02/28/76												
OOD	.00008	.00033	-	.00251	.18628	.92340	.40736	.35052	.17825	.23001	.45843	0
PD	.00017	.00001	-	.00021	<u>.73129</u>	<u>4.29441</u>	<u>2.84051</u>	.73800	<u>.05431</u>	.28655	.54113	<u>.00021</u>
Waukegan vs. Zion												
05/12/75-12/31/75												
CNL	-	-	-	-	2.82230	3.54028	1.00764	.28921	.30037	.65819	.15591	.04383
OOD	-	-	-	-	<u>96.09213</u>	<u>2.00108</u>	<u>.37212</u>	<u>.09750</u>	<u>.13301</u>	<u>.15247</u>	<u>.03238</u>	<u>.00286</u>
Lakeside vs. Port Washington												
03/07/75-02/26/76												
PD	0	0	0	.05499	.21484	1.01245	.25663	.05223	.00182	.00268	.12590	.01294
CNL	<u>.00582</u>	<u>.00087</u>	<u>.00167</u>	<u>.31192</u>	<u>12.90111</u>	<u>22.08029</u>	<u>6.81306</u>	<u>.96535</u>	<u>.14267</u>	<u>.69851</u>	<u>.27349</u>	<u>.03304</u>
Lakeside vs. Oak Creek												
03/07/75-02/06/76												
PD	0	0	0	.05499	.21484	1.01245	.25663	.05223	.00182	.00268	.12590	.01294
CNL	0	0	<u>.00149</u>	<u>.13458</u>	<u>2.77194</u>	<u>5.45543</u>	<u>3.00166</u>	<u>1.06960</u>	<u>.15047</u>	<u>.01571</u>	<u>.02490</u>	<u>.00415</u>
Bailey vs. Michigan City												
12/03/75-06/28/76												
PD	<u>.00042</u>	.00021	.00131	.12215	.78674	1.55160	-	-	-	-	-	.00117
CNL	0	.00016	<u>.55357</u>	<u>1.21574</u>	<u>2.14510</u>	<u>2.46038</u>	-	-	-	-	-	.00244
Oak Creek vs. Port Washington												
03/04/75-02/25/76												
CNL	0	0	.00133	.13458	2.77194	5.45543	3.00166	1.06960	.15047	.01571	.02490	.00415
CNL	<u>.00582</u>	<u>.01064</u>	.00161	.31192	<u>12.90111</u>	<u>22.08029</u>	<u>6.81306</u>	.96535	.14267	<u>.69851</u>	<u>.27439</u>	<u>.03304</u>
Mitchell vs. Stateline												
05/03/75-03/30/76												
PD	.00032	<u>.00045</u>	0	-	1.38272	1.02870	.18293	.01530	.00121	.00976	.66217	.13175
PD	.00028	0	0	-	<u>2.84351</u>	<u>2.05157</u>	<u>.48243</u>	.01315	<u>.02828</u>	<u>.00154</u>	<u>.00448</u>	<u>.00052</u>

cate that canal intakes impinge significantly more smelt/unit volume between April and September, while significantly higher densities are impinged by porous dikes in late fall, and by offshore open bays in early spring. Offshore intakes, as a group, impinge significantly higher densities of smelt from fall to early spring, while onshore intakes impinge higher densities in April and summer months. Figure 5 presents the annual mean impingement densities of smelt at each sampled intake and clearly indicates the relatively high abundance of smelt on the western shore of Lake Michigan: i.e., regardless of intake type, the highest annual densities of smelt occur at intakes on the Wisconsin and northern Illinois shores. On an annual basis, the mean density of smelt impinged at canal intakes is substantially higher than those at OOB and PD intakes, but this difference may be a result of the higher number of canal intakes on the western shore of the lake. The comparisons of monthly smelt impingement densities between "adjacent" pairs of intakes (Table 23) suggests that canal intakes impinge significantly more smelt than OOB or PD intakes throughout most of the year, with the exception of late fall (Zion vs. Waukegan). Porous dikes (Point Beach vs. Kewaunee) may impinge higher densities of young of the year in late summer. Comparisons of similar "adjacent" intakes show consistently higher densities at Oak Creek compared to Port Washington and seasonal differences between Mitchell and Stateline: i.e., between June and December the onshore porous dike at Stateline impinged fewer smelt/unit volume than the more offshore porous dike at Mitchell and, in late winter, the reverse was true.

Rainbow smelt eggs were entrained at significantly higher rates (densities) by offshore open bay intakes and by offshore intakes as a group (Table 19). The mean annual densities of entrained smelt eggs (Fig. 6) were highest at intakes on the southern basin of Lake Michigan and apparently were highest at OOB intakes. Unfortunately, the major period of smelt egg entrainment (early spring) either was not sampled by some utilities or was sampled in different years; therefore, the statistical comparisons between "adjacent" intakes were limited to very few months (Table 24). Despite these problems, the comparisons do indicate significantly higher densities of entrained smelt eggs at OOB intakes (Kewaunee vs. Point Beach and Zion vs. Waukegan).

Rainbow smelt larvae also were entrained at significantly higher rates (densities) by offshore open bay intakes and by offshore intakes as a group (Table 19). Intakes on the western shore and in the southern basin of Lake Michigan tended to show the highest densities of entrained smelt larvae (Fig. 7). Table 25 presents the comparisons of smelt larval densities between "adjacent" intakes and reflects the lakewide trend of offshore open bays entraining higher densities than canal or porous dike intakes. Although Port Washington entrained higher densities of smelt eggs than did Oak Creek, the reverse was true for smelt larvae. Mitchell's porous dike (more offshore) consistently entrained more smelt larvae/unit volume than did the onshore porous dike at Stateline.

In conclusion, the above analyses indicate that canal intakes are most destructive of smelt adults during the spawning season, while offshore porous dikes and open bays tend to impinge more smelt/unit volume during other periods of the year. Smelt eggs and larvae seem most susceptible to OOB intakes and offshore intakes in general.

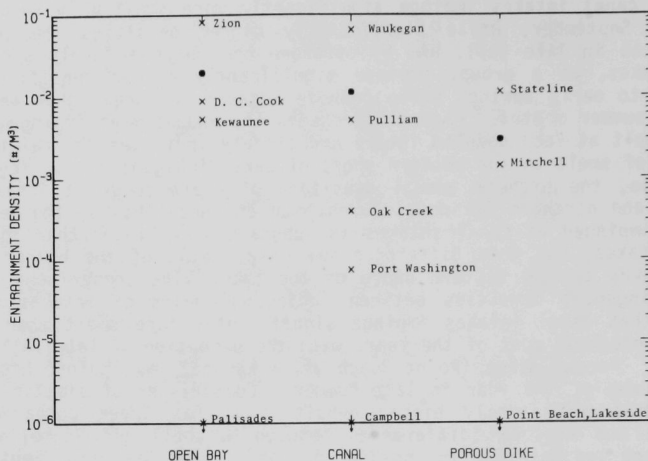


Fig. 6. Mean annual densities of entrained smelt eggs at each sampled intake (1975). Circles represents means for each intake type.

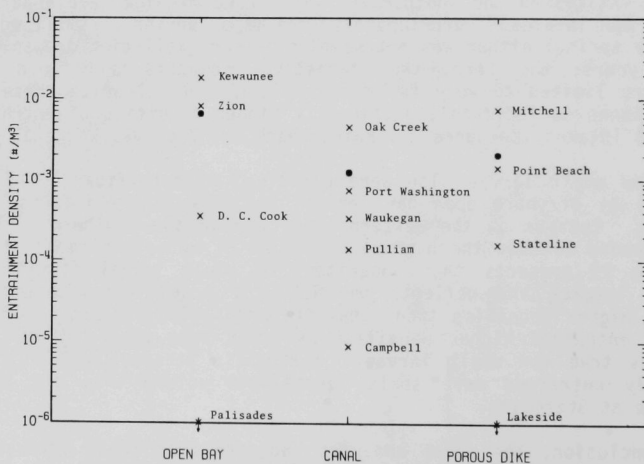


Fig. 7. Mean annual densities of entrained smelt larvae at each sampled intake (1975). Circles represent means for each intake type.

Table 21. Statistical comparisons of the monthly mean densities (N/m³) of entrained alewife eggs between dissimilar and similar intakes that are "adjacent" to one another. Underlined densities are significantly higher ($\alpha = 0.05$).

	January	February	March	April	May	June	July	August	September	October	November	December
Kewaunee vs. Point Beach												
04/18/75-10/31/75												
OOB	-	-	-	0	0	.01711	.56431	.09761	0	0	-	-
PD	-	-	-	0	0	.00450	.01987	.01097	0	0	-	-
Waukegan vs. Zion												
04/16/75-09/03/75												
CNL	-	-	-	0	.00587	24.34260	5.81448	.93701	.01435	-	-	-
OOB	-	-	-	0	.00244	1.88130	2.79794	.15977	0	-	-	-
Lakeside vs. Port Washington												
05/20/75-10/28/75												
PD	-	-	-	-	0	.01301	.05450	.00432	0	0	-	-
CNL	-	-	-	-	0	.00204	.03765	.00053	0	0	-	-
Lakeside vs. Oak Creek												
05/20/75-10/29/75												
PD	-	-	-	-	0	.01301	.05450	.00432	0	0	-	-
CNL	-	-	-	-	0	.00536	.01754	.02179	0	0	-	-
Oak Creek vs. Port Washington												
04/17/75-10/28/75												
CNL	-	-	-	0	0	.00536	.01754	.02179	0	0	-	-
CNL	-	-	-	0	0	.00204	.03765	.00053	0	0	-	-
Mitchell vs. Stateline												
05/03/75-09/04/75												
PD	-	-	-	-	3.31866	22.47867	5.86174	.11838	.01220	-	-	-
PD	-	-	-	-	.09453	4.71500	.82323	.19407	.00036	-	-	-

Table 22. Statistical comparisons of the monthly mean densities (N/m³) of entrained alewife larvae between dissimilar and similar intakes that are "adjacent" to one another. Underlined densities are significantly higher ($\alpha = 0.05$).

	January	February	March	April	May	June	July	August	September	October	November	December
Kewaunee vs. Point Beach												
04/18/75-10/31/75												
OOB	-	-	-	0	0	0	.00315	.00149	.00441	0	-	-
PD	-	-	-	0	0	0	.00019	.00109	.00129	.00003	-	-
Waukegan vs. Zion												
04/16/75-09/03/75												
CNL	-	-	-	0	0	.01927	.07355	.01658	.08063	-	-	-
OOB	-	-	-	0	0	.00321	.03184	.00493	.00250	-	-	-
Lakeside vs. Port Washington												
05/20/75-10/28/75												
PD	-	-	-	-	0	.00310	.01177	0	0	0	-	-
CNL	-	-	-	-	0	.00005	.00018	.00123	.00321	0	-	-
Lakeside vs. Oak Creek												
05/20/75-10/29/75												
PD	-	-	-	-	0	.00310	.01177	0	0	0	-	-
CNL	-	-	-	-	0	0	.00002	.00253	.00770	.00056	-	-
Oak Creek vs. Port Washington												
04/17/75-10/28/75												
CNL	-	-	-	0	0	0	.00002	.00253	.00770	.00057	-	-
CNL	-	-	-	0	0	.00004	.00018	.00123	.00321	0	-	-
Mitchell vs. Stateline												
05/03/75-09/04/75												
PD	-	-	-	-	.00025	.08821	.04038	.01525	.00012	-	-	-
PD	-	-	-	-	0	.01227	.00571	.00546	.00169	-	-	-

Table 23. Statistical comparisons of the monthly mean densities (N/1000 m³) of impinged smelt between dissimilar and similar intakes that are "adjacent" to one another. Underlined densities are significantly higher ($\alpha = 0.05$).

	January	February	March	April	May	June	July	August	September	October	November	December
Kewaunee vs. Point Beach												
04/01/75-02/28/76												
DOB	.04948	.04481	-	.03899	.00353	.01754	.01261	.01185	.02228	.23001	.08779	.01459
PD	<u>.08043</u>	<u>.01966</u>	-	.00990	.00572	.01899	<u>.06966</u>	<u>.06159</u>	<u>.05637</u>	.28655	.18391	<u>.05555</u>
Waukegan vs. Zion												
05/12/75-12/31/75												
CNL	-	-	-	-	.00183	.00469	.02168	.00385	.00183	.00338	.00144	.00398
DOB	-	-	-	-	0	0	<u>.00061</u>	<u>.00078</u>	<u>.00090</u>	<u>.00128</u>	<u>.00637</u>	<u>.07176</u>
Lakeside vs. Port Washington												
03/07/75-02/06/76												
PD	.00014	.00164	0	0	.00118	.00121	0	0	0	.00045	.00188	0
CNL	<u>.00951</u>	<u>.00638</u>	<u>.03850</u>	<u>.12074</u>	<u>.10360</u>	<u>.10309</u>	<u>.20519</u>	<u>.29830</u>	<u>.45350</u>	<u>.00699</u>	<u>.03149</u>	<u>.03948</u>
Lakeside vs. Oak Creek												
03/07/75-02/06/76												
PD	.00014	.00164	0	0	.00118	.00121	0	0	0	.00045	.00188	0
CNL	<u>.02838</u>	<u>.04445</u>	<u>.09196</u>	<u>.73320</u>	<u>.31172</u>	<u>.19883</u>	<u>.69027</u>	<u>.39366</u>	<u>.21710</u>	<u>.03461</u>	<u>.12181</u>	<u>.08033</u>
Bailly vs. Michigan City												
12/03/75-06/28/76												
PD	.00042	.00018	.00370	.00649	.01014	.00016	-	-	-	-	-	.00072
CNL	.00042	<u>.00111</u>	.00284	.00449	.00763	<u>.00057</u>	-	-	-	-	-	.00056
Oak Creek vs. Port Washington												
03/04/75-02/25/76												
CNL	<u>.02838</u>	<u>.06124</u>	<u>.09001</u>	<u>.73320</u>	<u>.31172</u>	<u>.19883</u>	<u>.69027</u>	<u>.39366</u>	<u>.21710</u>	<u>.03461</u>	<u>.12181</u>	<u>.08033</u>
CNL	<u>.00951</u>	<u>.01068</u>	<u>.03489</u>	<u>.12074</u>	<u>.10360</u>	<u>.10309</u>	<u>.20519</u>	<u>.29830</u>	<u>.45350</u>	<u>.00699</u>	<u>.03149</u>	<u>.03948</u>
Mitchell vs. Stateline												
05/03/75-03/30/76												
PD	.00034	.00010	.00010	-	.00052	.00095	.00121	.00076	.00073	.00026	.00009	.00164
PD	.00036	<u>.00069</u>	<u>.00079</u>	-	.00054	<u>.00006</u>	<u>.00016</u>	<u>.00005</u>	0	<u>.00008</u>	.00005	<u>.00001</u>

Table 24. Statistical comparisons of the monthly mean densities (N/m^3) of entrained smelt eggs between dissimilar and similar intakes that are "adjacent" to one another. Underlined densities are significantly higher ($\alpha = 0.05$).

	January	February	March	April	May	June	July	August	September	October	November	December
Kewaunee vs. Point Beach												
04/18/75-10/31/75												
OOD	-	-	-	.05362	<u>.01422</u>	0	0	0	0	0	-	-
PD	-	-	-	0	0	0	0	0	0	0	-	-
Waukegan vs. Zion												
04/16/75-09/03/75												
CNL	-	-	-	.47900	.06609	0	0	0	0	-	-	-
OOD	-	-	-	<u>.62093</u>	.11037	.00061	0	0	0	-	-	-
Lakeside vs. Port Washington												
05/20/75-10/28/75												
PD	-	-	-	-	0	0	0	0	0	0	-	-
CNL	-	-	-	-	<u>.00210</u>	0	0	0	0	0	-	-
Lakeside vs. Oak Creek												
05/20/75-10/29/75												
PD	-	-	-	-	0	0	0	0	0	0	-	-
CNL	-	-	-	-	0	0	0	0	0	0	-	-
Oak Creek vs. Port Washington												
04/17/75-10/28/75												
CNL	-	-	-	0	.00048	0	0	0	0	0	-	-
CNL	-	-	-	.00005	<u>.00249</u>	0	0	0	0	0	-	-
Mitchell vs. Stateline												
05/03/75-09/04/75												
PD	-	-	-	-	.00681	0	0	0	0	-	-	-
PD	-	-	-	-	.00716	<u>.00068</u>	0	0	0	-	-	-

Table 25. Statistical comparisons of the monthly mean densities (N/m³) of entrained smelt larvae between dissimilar and similar intakes that are "adjacent" to one another. Underlined densities are significantly higher ($\alpha = 0.05$).

	January	February	March	April	May	June	July	August	September	October	November	December
Kewaunee vs. Point Beach												
04/18/75-10/31/75												
OOB	-	-	-	.00046	<u>.02027</u>	<u>.00169</u>	<u>.02555</u>	<u>.01206</u>	<u>.03186</u>	<u>.03551</u>	-	-
PD	-	-	-	0	0	0	0	<u>.00538</u>	<u>.00180</u>	<u>.00233</u>	-	-
Waukegan vs. Zion												
04/16/75-09/03/75												
CNL	-	-	-	0	.00053	.00100	0	0	0	-	-	-
OOB	-	-	-	0	<u>.03555</u>	<u>.00492</u>	0	0	0	-	-	-
Lakeside vs. Port Washington												
05/20/75-10/28/75												
PD	-	-	-	-	0	0	0	0	0	0	-	-
CNL	-	-	-	-	0	0	<u>.00026</u>	<u>.00149</u>	<u>.00298</u>	0	-	-
Lakeside vs. Oak Creek												
05/20/75-10/29/75												
PD	-	-	-	-	0	0	0	0	0	0	-	-
CNL	-	-	-	-	0	<u>.00021</u>	<u>.00021</u>	<u>.01518</u>	<u>.00837</u>	<u>.00152</u>	-	-
Oak Creek vs. Port Washington												
04/17/75-10/28/75												
CNL	-	-	-	0	<u>.00048</u>	<u>.00021</u>	<u>.00286</u>	<u>.01518</u>	<u>.00837</u>	<u>.00156</u>	-	-
CNL	-	-	-	0	0	0	<u>.00026</u>	<u>.00149</u>	<u>.00298</u>	0	-	-
Mitchell vs. Stataline												
05/03/75-09/04/75												
PD	-	-	-	-	<u>.02996</u>	0	<u>.00117</u>	<u>.00365</u>	<u>.00012</u>	-	-	-
PD	-	-	-	-	<u>.00025</u>	0	<u>.00001</u>	<u>.00054</u>	0	-	-	-

Yellow Perch

The results of statistical comparisons for yellow perch impingement between intake types (Table 18) are highly affected by the disproportionate impingement density at the Pulliam plant (onshore canal intakes). Figure 8 presents the annual perch impingement densities at each sampled intake and indicates that, if Pulliam is excluded, offshore open bay intakes and any type sited on the southeastern shore of Lake Michigan impinge the highest densities of yellow perch. Comparisons of "adjacent" plants (Table 26) indicate the OOB and canal intakes impinged more yellow perch/unit volume than do porous dike intakes, and that the canal intake at Waukegan impinged higher densities of perch than the OOB intake at Zion. No consistent differences were observed between the "adjacent" canal intakes or between the "adjacent" porous dike intakes.

Yellow perch eggs were not identified at some and not found at other sampled intakes, making a statistical comparison difficult. The annual mean density of perch eggs at D. C. Cook was similar to that at Pulliam (Fig. 9) despite the order of magnitude difference between perch impingements at these plants, indicating that OOB intakes might entrain significantly higher densities, if inshore abundances were equal. Based on the very limited data in Figure 10, it appears that canal intakes are at least as destructive of yellow perch larvae as are OOB intakes, if Pulliam is excluded.

Effects of Flow and Geographic Location

Generally, it is assumed that the numbers of fish impinged or entrained by water intakes are directly related to the water flow or quantity withdrawn. A "perfect" linear relationship between these variables (i.e., where all the variability in y is explained by the variability in x) would require homogeneous distribution of the fish species/life stage throughout the body of water, as well as no site-specific, intake-related differences in impingement/entrainment rates. It is clear from the preceding analyses that neither of these requirements are true for any of the three Lake Michigan species included in this report.

Since the sampling of power plant intakes was planned and executed in a site-specific manner, the available data do not provide adequate representation of the variables potentially affecting impingement and entrainment values: i.e., a stratified or hierarchical sampling design would be required to estimate the individual effects of intake type, location, fish abundance, and flow. Despite these apparent problems, we performed linear regressions (log observed impingement/entrainment vs. log observed flow) for each species/lifestage to estimate the effects of flow and to determine the feasibility of predicting the effects of future water intakes.

The effect of water intake flow on impingement of alewife is shown in Figure 11. A strong linear (log-log) relationship was found ($P \leq 0.0001$) and the results indicate that 66% of the variability in impingement ($R^2 = 0.66$) is associated with flow. It is apparent from this plot that four intakes impinged inordinately high numbers of alewife: Zion (1), Port Washington (8), Pulliam (5), and Michigan City (4). The aforementioned effects of canal intakes and western shore locations are substantiated. This indicates that a canal intake sited on the western shore of Lake Michigan or on Green Bay could

Table 26. Statistical comparisons of the monthly mean densities (N/1000 m³) of impinged yellow perch between dissimilar and similar intakes that are "adjacent" to one another. Underlined densities are significantly higher ($\alpha = 0.05$).

	January	February	March	April	May	June	July	August	September	October	November	December
Kewaunee vs. Point Beach												
04/01/75-02/28/76												
00B	0	.00009	-	.00034	.00014	.00054	.00086	.00040	.00053	.00029	.00050	.00017
PD	<u>.00007</u>	.00004	-	.00059	.00006	<u>.00008</u>	<u>.00032</u>	.00027	.00028	.00020	<u>.00018</u>	.00021
Waukegan vs. Zion												
05/12/75-12/31/75												
CNL	-	-	-	-	.00005	0	.00009	.00027	.00108	.00113	.00003	.00050
00B	-	-	-	-	0	0	.00010	<u>.00020</u>	<u>.00018</u>	<u>.00009</u>	<u>.00042</u>	<u>.00006</u>
Lakeside vs. Port Washington												
03/07/75-02/06/76												
PD	0	0	0	0	0	.00002	.00032	.00010	0	0	0	0
CNL	0	<u>.00054</u>	<u>.00086</u>	<u>.00113</u>	<u>.00040</u>	<u>.00054</u>	<u>.00078</u>	<u>.00044</u>	<u>.00018</u>	<u>.00007</u>	<u>.00046</u>	<u>.00020</u>
Lakeside vs. Oak Creek												
03/07/75-02/06/76												
PD	0	0	0	0	0	.00002	.00032	.00010	0	0	0	0
CNL	<u>.00052</u>	<u>.00039</u>	<u>.00219</u>	<u>.00107</u>	<u>.00020</u>	.00010	<u>.00411</u>	<u>.00039</u>	<u>.00021</u>	0	<u>.00027</u>	<u>.00105</u>
Baillly vs. Michigan City												
12/03/75-06/28/76												
PD	<u>.00200</u>	.00020	.00068	.00029	0	.00029	-	-	-	-	-	.00109
CNL	0	<u>.00156</u>	<u>.00201</u>	<u>.00346</u>	<u>.00631</u>	<u>.00188</u>	-	-	-	-	-	.00178
Oak Creek vs. Port Washington												
03/04/75-02/25/76												
CNL	<u>.00052</u>	.00009	.00207	.00107	.00020	.00010	.00411	.00039	.00021	0	.00027	.00105
CNL	0	.00013	<u>.00077</u>	.00113	<u>.00040</u>	<u>.00054</u>	<u>.00078</u>	.00044	.00018	<u>.00007</u>	.00046	<u>.00020</u>
Mitchell vs. Stateline												
05/03/75-03/30/76												
PD	.00040	.00003	.00052	-	0	.00024	.00307	.00437	.00028	0	.00008	.00080
PD	<u>.00028</u>	<u>.00037</u>	<u>.00013</u>	-	<u>.00027</u>	<u>.00097</u>	.00419	.00288	.00037	<u>.00031</u>	.00005	<u>.00004</u>

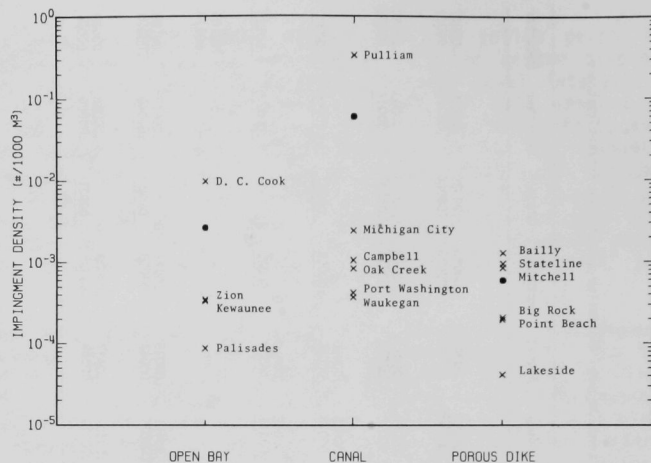


Fig. 8. Mean annual densities of impinged yellow perch at each sampled intake (1975). Circles represent means for each intake type.

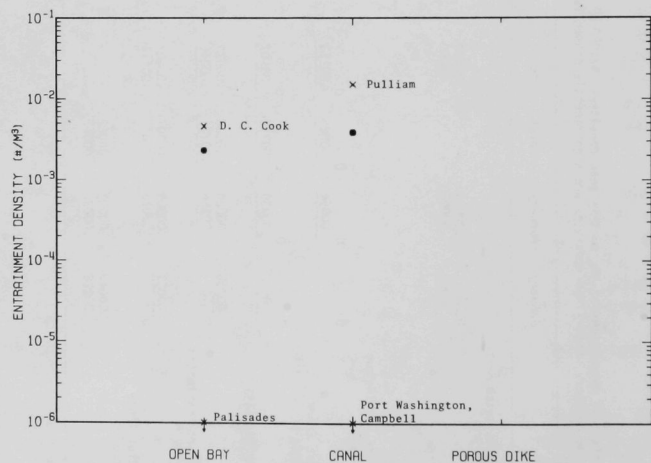


Fig. 9. Mean annual densities of entrained yellow perch eggs at each sampled intake (1975). Circles represent means for each intake type.

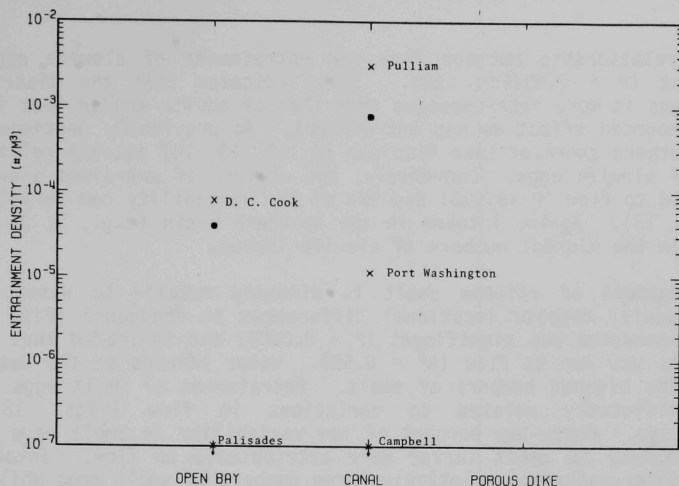


Fig. 10. Mean annual densities of entrained yellow perch larvae at each sampled intake (1975). Circles represent means for each intake type.

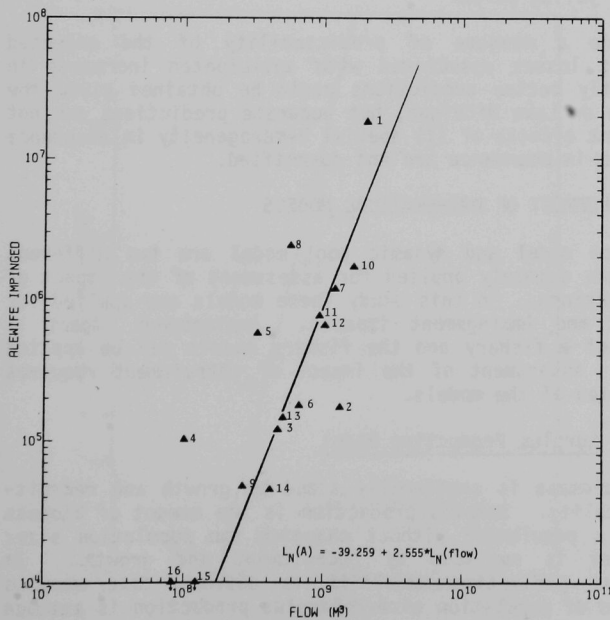


Fig. 11. Relationship between total number of alewife impinged and total flow (1975).

impinge ten times the number of alewife as another intake type sited elsewhere.

The relationship between flow and entrainment of alewife eggs was not significant ($P > 0.6$) (Fig. 12). This indicates that the distribution of alewife eggs is more heterogeneous than that of adults and/or that intake type has a pronounced effect on egg entrainment. As previously mentioned, intakes on the southern shore of Lake Michigan (3, 11, 13, 12) entrain relatively high numbers of alewife eggs. Conversely, the numbers of entrained alewife larvae are related to flow ($P < 0.003$) and 52% of the variability can be attributed to flow (Fig. 13). Again, intakes in the southern basin (e.g., 2, 3, 11, 13, 1, 12) entrain the highest numbers of alewife larvae.

Impingement of rainbow smelt is directly related to water flow on a lakewide basis, despite locational differences in abundance (Fig. 14). The log-log regression was significant ($P = 0.0005$) and indicated that 59% of the variability was due to flow ($R^2 = 0.59$). Water intakes on the western shore impinged the highest numbers of smelt. Entrainment of smelt eggs and larvae were significantly related to variations in flow (Figs. 15 and 16, respectively). Forty-two percent of the variability in smelt eggs and 56% of the variability in smelt larvae were attributable to flow. Intakes on the southern shore entrained relatively large numbers of smelt eggs while southern and western intakes entrained large numbers of larvae.

Impingement of yellow perch was significantly related to flow on a lakewide basis if the Pulliam intake (5) was excluded (Fig. 17). Intakes in Green Bay (5) and in the southern basin of Lake Michigan (2, 12, 3, 13, 1) impinged relatively high numbers of yellow perch.

Figures 11-17 provide a measure of predictability of the expected impingement or entrainment losses associated with anticipated increases in water withdrawals. Slightly better predictions could be obtained given the intake design and location on Lake Michigan, but accurate predictions are not possible since the important effects of (1) spatial heterogeneity in abundance and (2) annual fluctuations in abundance are not quantified.

DEVELOPMENT OF MATHEMATICAL MODELS

The surplus production model and dynamic pool model are two different mathematical models that are commonly applied for assessment of the impact of exploitation on fish populations. In this study these models are applied for assessment of entrainment and impingement impacts. Impingement impact is comparable to the impact of a fishery and the fishery models can be applied with little modification. Assessment of the impact of entrainment requires more substantial modification of the models.

Surplus Production Model

In all populations, biomass is continually added by growth and recruitment and lost through mortality. Surplus production is the amount of biomass that can be removed from a population without changing the population size: i.e., the biomass removed is replaced by recruitment and growth. In derivation of the surplus production model it is assumed that surplus production is some function of population size. Surplus production is assumed

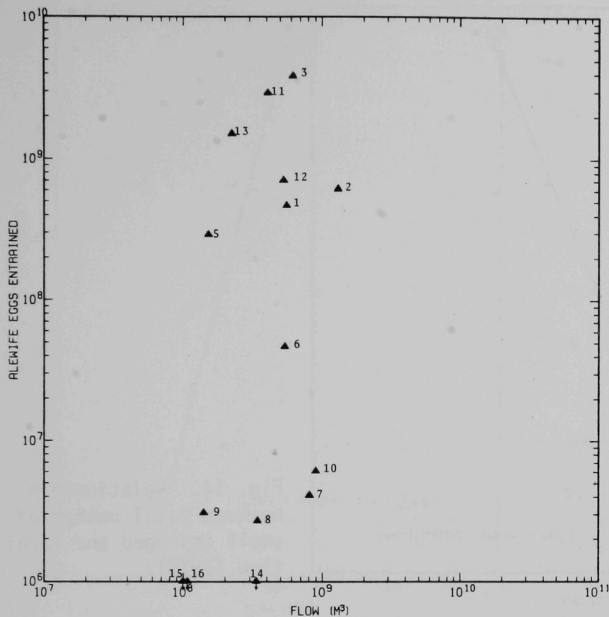


Fig. 12. Relationship between total number of alewife eggs entrained and total flow (1975).

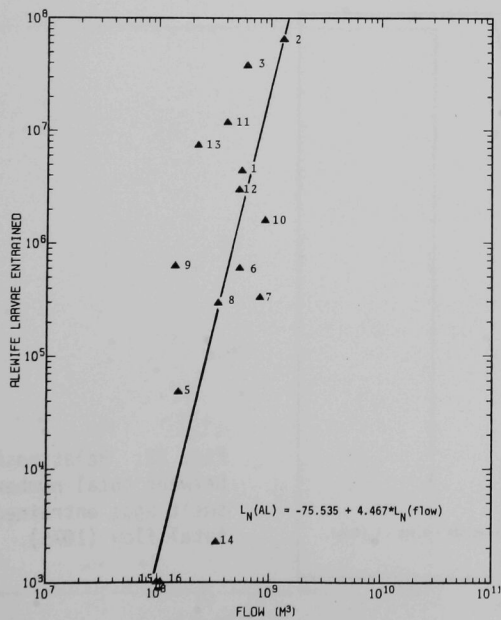


Fig. 13. Relationship between total number of alewife larvae entrained and total flow (1975).

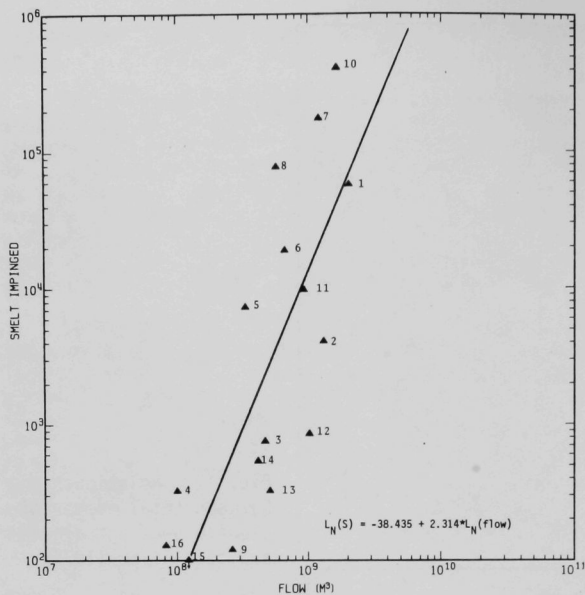


Fig. 14. Relationship between total number of smelt impinged and total flow (1975).

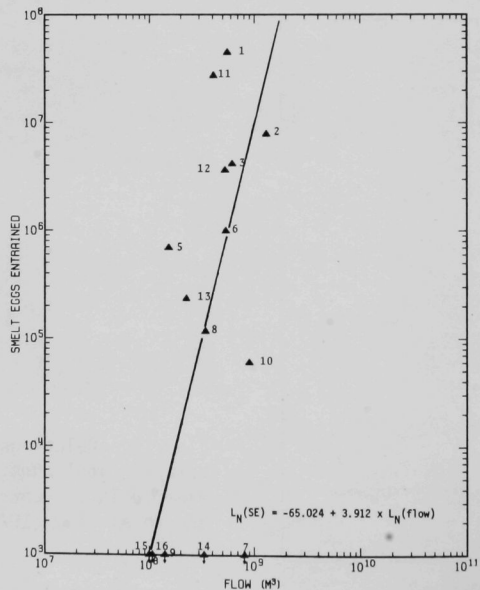


Fig. 15. Relationship between total number of smelt eggs entrained and total flow (1975).

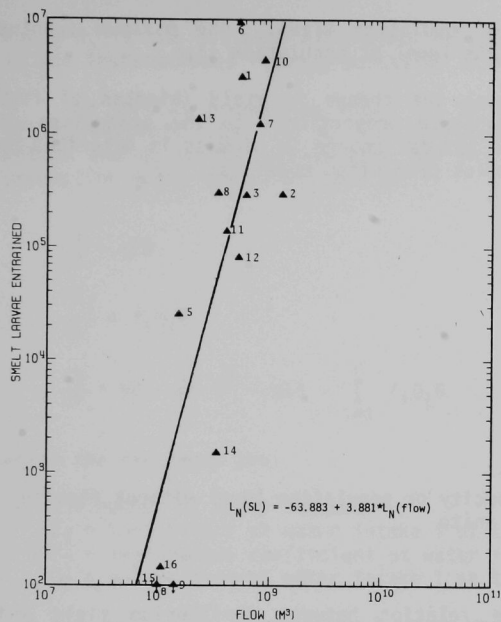


Fig. 16. Relationship between total number of smelt larvae entrained and total flow (1975).

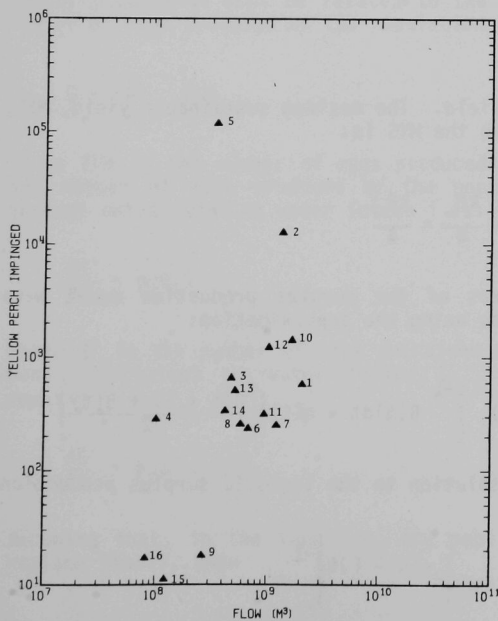


Fig. 17. Relationship between total number of yellow perch impinged and total flow (1975).

to be small at both high and low population sizes. The maximum surplus production occurs at some intermediate level of population size.

In the surplus production model the change in yield (biomass of fish caught) with respect to time is assumed proportional to the production of biomass and fishing effort. If the natural change in biomass is described by the logistic equation, then the surplus production model is:

$$\frac{dY}{dt} = qEB$$

$$\frac{dB}{dt} = kB - \frac{k}{B_{\infty}} B^2 - qEB$$

where:

Y = yield in kg

B = population biomass in kg

k = population growth parameter

B_{∞} = environmental carrying capacity or population level without fishing

E = fishing effort in standard units

q = catchability coefficient

t = time in years.

Under equilibrium conditions, the relation between equilibrium yield and biomass is the parabola

$$Y_e = kB - \frac{k}{B_{\infty}} B^2$$

where Y_e is the annual equilibrium yield. The maximum sustainable yield, MSY, occurs at a biomass level of $B_{\infty}/2$, so the MYS is:

$$MSY = k \frac{B_{\infty}}{2} - \frac{k}{B_{\infty}} \left(\frac{B_{\infty}}{2} \right)^2 = \frac{2kB_{\infty}}{4} - \frac{kB_{\infty}^2}{4} = \frac{kB_{\infty}}{4}$$

For each species the parameters of the surplus production model were estimated by non-linear least squares using the approximation:

$$Y_a(t) = Y(t+1) - Y(t) = qE(t) \int_t^{t+1} B(t)dt \approx qE(t) \left[\frac{B(t+1) + B(t)}{2} \right]$$

where Y_a is the annual yield. The solution to the logistic surplus production model is:

$$B(t) = \left\{ \frac{k}{B_{\infty}(k-F)} + \left[\frac{1}{B_0} - \frac{k}{B_{\infty}(k-F)} \right] e^{-(k-F)t} \right\}^{-1}$$

where B_0 is the estimate of biomass in 1960 obtained as $1/q$ (1960 CPUE) and F is the instantaneous fishing mortality coefficient.

The surplus production model can be modified easily to model the impact of impingement. Let f_i be the impingement coefficient for the i^{th} water intake and Q_i be the volume flow for the i^{th} water intake; then the surplus production model can be written as:

$$\frac{dY}{dt} = qEB$$

$$\frac{dI_i}{dt} = f_i Q_i B$$

$$\frac{dB}{dt} = kB - \frac{k}{B_\infty} B^2 - qEB - \sum_{i=1}^n f_i Q_i B$$

where the new terms are:

n = number of water intakes

I_i = impingement at water intake i at time t

f_i = impingement coefficient at water intake i

Q_i = volume flow at water intake i at time t .

To apply the surplus production model for assessment of entrainment, equations must be developed for egg production and for larval production; then larval production must be related to the biomass of the standing stock. The number of eggs produced by the population, G , is:

$$G = \frac{B}{2} \text{ EUB}$$

where EUB is the number of eggs produced per unit of female biomass and G is the number of eggs produced by the population. The rate of loss of eggs through entrainment at water intake i is:

$$\frac{dG'}{dt} = p_i Q_i G$$

where G' is the number of eggs entrained at time t and p_i is the egg entrainment coefficient at water intake i . Substitution from above gives the equation:

$$\frac{dG'}{dt} = p_i Q_i \frac{B}{2} \text{ EUB}.$$

Assuming that, in the long run, the population produces enough eggs to just replace itself, then

$$\left(\frac{dB}{dt}\right)_e = \frac{2}{EUB} \frac{dG'}{dt}.$$

where $(dB/dt)_e$ is the rate of biomass loss as a result of egg entrainment. The amount of biomass produced is a function of the number of eggs produced. The impact of entrainment on egg is equivalent to a reduction in egg production by the population. The rate of biomass loss resulting from egg entrainment, $(dB/dt)_e$, is

$$\left(\frac{dB}{dt}\right)_e = p_i Q_i B.$$

Now the impact of larval entrainment on biomass production will be determined. The number of larvae produced by G eggs is:

$$L = (1 - \phi)G$$

where L is the number of larvae produced from G eggs and ϕ is the mortality from the egg stage to the larval stage. The relation between adult biomass and the number of larvae produced is given by the equation

$$L = (1 - \phi) \frac{EUB}{2} B.$$

Differentiation of this equation with respect to time gives

$$\frac{dL}{dt} = (1 - \phi) \frac{EUB}{2} \frac{dB}{dt}$$

and the rate of change in biomass resulting from entrainment of larvae at the i^{th} water intake, $(dB/dt)_l$, is

$$\left(\frac{dB}{dt}\right)_l = \frac{dL'/dt}{(1 - \phi) \frac{EUB}{2}}$$

where dL'/dt is the rate of larval entrainment at the water intake. The rate of larval entrainment at water intake i can be modeled with the equation

$$\frac{dL'}{dt} = h_i Q_i L$$

where h_i is the larval entrainment coefficient at water intake i . Combination of the above equations for larval entrainment gives the rate of biomass change resulting from larval entrainment at water intake i as

$$\left(\frac{dB}{dt}\right)_1 = h_i Q_i B$$

Combining the above equations for egg and larval entrainment gives the following surplus production model for assessment of entrainment impact:

$$\frac{dY}{dt} = qEB$$

$$\frac{dL'}{dt} = \sum_{i=1}^n p_i Q_i B$$

$$\frac{dG'}{dt} = \sum_{i=1}^n h_i Q_i B$$

$$\frac{dB}{dt} = kB - \frac{k}{B_{\infty}} B^2 - qEB - \sum_{i=1}^n p_i Q_i B - \sum_{i=1}^n h_i Q_i B.$$

Combining the model for entrainment and impingement impact gives the model

$$\frac{dY}{dt} = qEB$$

$$\frac{dI}{dt} = \sum_{i=1}^n f_i Q_i B$$

$$\frac{dG'}{dt} = \sum_{i=1}^n p_i Q_i B$$

$$\frac{dL'}{dt} = \sum_{i=1}^n h_i Q_i B$$

$$\frac{dB}{dt} = kB - \frac{k}{B_{\infty}} B^2 - qEB - \sum_{i=1}^n f_i Q_i B - \sum_{i=1}^n p_i Q_i B - \sum_{i=1}^n h_i Q_i B.$$

This model was applied to study the combined impacts of impingement and entrainment on standing stocks and maximum sustainable yields of alewife, perch, and smelt.

Dynamic Pool Model

The dynamic pool model [28] provides a more complete and detailed description of the dynamics of a population than does the surplus production

model [29]. The dynamic pool model is a reductionistic model in which the yield from a fishery is broken into its components: growth, reproduction, and mortality. Each of these components is modeled separately, in as great a detail as necessary, and then the components are brought together into a model for yield.

The derivation of the dynamic pool model begins with the identity relating the biomass of a cohort to the number of individuals and average individual weight. The biomass of a cohort at age x , $B(x)$, is the product of the number of individuals of age x , $N(x)$, and the average weight of an individual of age x , $W(x)$:

$$B(x) = N(x) \cdot W(x).$$

Differentiation of this equation gives the change in biomass with respect to age as

$$\frac{dB(x)}{dx} = N(x) \frac{dW(x)}{dx} + W(x) \frac{dN(x)}{dx}.$$

The first term on the right relates to production and the second term to the loss of biomass by mortality. Yield to a fishery equals the loss due to fishing:

$$\frac{dY}{dx} = -W(x) \left(\frac{dN(x)}{dx} \right)_F$$

where $(dN(x)/dx)_F$ is fishing mortality. It is usually assumed that

$$\left(\frac{dN(x)}{dx} \right)_F = -FN(x),$$

where F is the instantaneous fishing mortality coefficient and the yield equation then becomes

$$\frac{dY}{dx} = F N(x) W(x).$$

To apply this model, relations for $W(x)$ and $N(x)$ as functions of age must be developed. Assume that fish are recruited into the exploited stock at age x_c ; then if mortality follows the exponential model, change in cohort size is given by the equations:

$$\frac{dN}{dx} = -MN, \quad x_r < x < x_c$$

$$\frac{dN}{dt} = -(F + M)N, \quad x > x_c.$$

Solution of these equations gives the mortality equation

$$N(x) = Re^{-M(x_c - x_r) - (F + M)(x - x_c)}, x > x_r$$

where:

M = instantaneous natural mortality coefficient

x_c = age at entry to fishery

x_r = age at recruitment

R = number of recruits.

To model weight as a function of age, it is usual to begin with an equation for length as a function of age. Growth in length is asymptotic and can usually be described accurately by the equation:

$$l(x) = l_{\infty}(1 - e^{-K(x - x_0)})$$

where:

$l(x)$ = length at age x

l_{∞} = asymptotic length

K = growth constant

x_0 = age when length equals zero (assumed to be zero).

The relation between length and weight is accurately described by the parabolic growth equation

$$W(x) = a l(x)^b$$

where a and b are constants. For simplicity it will be assumed that $b = 3$. Substitution of the equation for length as a function of age into the length-weight equation gives the equation for growth in weight as

$$W(x) = W_{\infty}(1 - e^{-K(x - x_0)})^3,$$

where W_{∞} = asymptotic individual weight. This is von Bertalanffy's growth equation [9].

Combining the above results for mortality and growth gives the yield equation:

$$\frac{dY}{dx} = FW_{\infty}Re^{-M(x_c - x_r) - (F + M)(x - x_c)}(1 - e^{-K(x - x_0)})^3.$$

The solution of the equation is

$$Y = RW_{\infty} e^{-M(x_c - x_r)} \sum_{j=0}^3 \frac{U_j e^{-jK(x_c - x_0)}}{F + M + jK}$$

where: $U_0 = 1$, $U_1 = -3$, $U_2 = 3$, and $U_3 = -1$ (integration constants).

Modification of the dynamic pool model for assessment of impingement impact is straightforward. The rate of impingement with respect to age (time) is:

$$\frac{dI}{dx} = f_i Q_i N(x) W(x).$$

The mortality equation modified to include the impact of n water intakes is

$$N(x) = R e^{-(M + \sum_{i=1}^n f_i Q_i)(x_c - x_I) - (F + M + \sum_{i=1}^n f_i Q_i)(x - x_c)}$$

where the new term is: x_I = age when fish first become vulnerable to impingement. The biomass of a cohort subject to impingement loss is

$$B = RW_{\infty} e^{-(M + \sum_{i=1}^n f_i Q_i)(x_c - x_I)} \sum_{j=0}^3 \frac{U_j e^{-jK(x_c - x_0)}}{F + M + \sum_{i=1}^n f_i Q_i + jK}$$

and the yield from the fishery under equilibrium conditions is

$$Y_e = FB.$$

To apply the above equations the number of recruits must be determined. Application of the catch equation,

$$\frac{dC}{dx} = F N(x),$$

(where C is the annual catch from the fishery) together with the mortality equation gives:

$$R = \frac{(M + F + \sum_{i=1}^n f_i Q_i) C e^{(M + \sum_{i=1}^n f_i Q_i)(x_c - x_I)}}{F}$$

Additional modifications of the dynamic pool model are necessary to apply the model for assessment of entrainment. The number of eggs produced annually in a steady state is:

$$G = \text{EUB} \frac{B}{2}.$$

These eggs are subject to natural and entrainment mortality so an equation for change in the numbers of eggs is:

$$\frac{dG}{dx} = -(M_1 + \sum_{i=1}^n p_i Q_i) G$$

where:

M_1 = natural mortality coefficient for egg stage.

The number of larvae produced by an initial number of eggs, $G(0)$, is

$$L(0) = G(0) e^{-(M_1 + \sum_{i=1}^n p_i Q_i) \Delta t_1}$$

where:

$L(0)$ = number of larvae produced by a cohort

$G(0)$ = initial number of eggs produced by a cohort

Δt_1 = duration of time from spawning to larval stage (after yolk sac has been adsorbed).

Larvae are subject to natural mortality and entrainment mortality; thus, the equation for change in the number of larvae is:

$$\frac{dL}{dx} = -(M_2 + \sum_{i=1}^n h_i Q_i) L$$

where:

M_2 = larval mortality coefficient.

Combining the above equations for egg production, egg mortality, and larval mortality gives the following equation for the number of recruits:

$$R = G(0)e^{-(M_1 + \sum_{i=1}^n p_i Q_i) \Delta t_1 - (M_2 + \sum_{i=1}^n h_i Q_i) \Delta t_2}$$

where Δt_2 is the duration of time from first entry into the larval stage to the young-of-year stage.

The impact of entrainment on standing stock and yield will be a result of its impact on recruitment.

ESTIMATION OF BIOLOGICAL AND FISHING PARAMETERS

Surplus Production Model

For the surplus production model the catchability coefficient, q , population growth parameter, k , and carrying capacity, B_∞ , were estimated by non-linear least squares using the commercial catch and effort data. Lake Michigan has been divided into 16 fishery statistical districts (Fig. 1) and data on catch and effort are obtained annually for each district. In this study data for the years 1960 to 1977 were applied for estimation of model parameters.

For each species the parameters of the surplus production model were estimated by non-linear least squares using the approximation

$$Y_a(t) = Y(t+1) - Y(t) = qE(t) \int_t^{t+1} B(t) dt \approx qE(t) \left[\frac{B(t+1) + B(t)}{2} \right]$$

and the solution to the logistic surplus production model is:

$$B(t) = \left[\frac{k}{B_\infty(k-F)} + \left[\frac{1}{B_0} - \frac{k}{B_\infty(k-F)} \right] e^{-(k-F)t} \right]^{-1}$$

where B_0 is the estimate of biomass in 1960 obtained as $1/q$ (1960 CPUE).

Alewife

The major fishing methods applied for alewife were trawls and pound nets. Pound nets are used more widely than trawls; therefore, total effort was expressed in terms of pound nets. Total effort in terms of a standard gear was calculated as

$$\text{total effort} = \frac{\text{total catch}}{\text{CPUE with standard gear}}$$

where CPUE = catch per unit effort. The total catch and effort data for alewife in Lake Michigan are listed in Table 27. For alewife the model parameters are:

$q = 0.00001$
 $k = 0.30$
 $B_{\infty} = 400,000,000 \text{ kg.}$

The fit of the observed yields to the predicted yields is good in recent years (Fig. 18), and for 1975 the observed yield is close to the predicted yield. In 1963 the model predicts a much higher yield than was observed and in 1967 the model predicts a much lower yield than was observed. From 1968 to 1977 the predictions are good except for 1973 when the prediction was somewhat high. Substantial changes have occurred in the fishery since 1960 with large variations in population size and massive die-offs.

The maximum sustainable yield occurs at a biomass level of about 200,000,000 kg and is about 30,000,000 kg (Fig. 19). The maximum observed catch of 21,959,080 kg occurred in 1977. The alewife population does not appear to be over-exploited by the fishery but the level of exploitation is substantial.

Table 27. Total catch (kg), pound net effort (number of lifts), and catch per unit of effort for alewife in Lake Michigan, 1960-1977.

Year	Catch	Effort	CPUE
1960	1057103	2621	403.26
1961	1449346	2327	622.71
1962	3456625	8501	406.58
1963	2448165	24582	99.59
1964	5326641	11546	461.32
1965	6353358	7425	855.60
1966	13155789	12118	1085.57
1967	19054064	16742	1138.06
1968	12285364	11462	1071.77
1969	13330230	10050	1326.32
1970	15114488	10203	1481.28
1971	13450181	7599	1769.92
1972	14076502	7767	1812.34
1973	16584780	11872	1396.85
1974	20663696	10131	2039.52
1975	15961428	7730	2064.81
1976	17786288	7918	2246.07
1977	21959808	7931	2768.55

Table 28. Total catch (kg), trap net effort (number of lifts), and catch per unit of effort for yellow perch in Lake Michigan, 1960-1977.

Year	Catch	Effort	CPUE
1960	1489562	57444	25.93
1961	2574813	98958	26.02
1962	2039568	59269	34.41
1963	2210172	50186	44.04
1964	2646878	91459	28.94
1965	695885	49878	13.95
1966	406440	30426	13.36
1967	573967	27501	20.87
1968	235669	15364	15.34
1969	291719	15719	18.56
1970	313820	17628	17.80
1971	338270	18324	18.46
1972	465686	20050	23.23
1973	339997	20372	16.69
1974	587902	32909	17.86
1975	344354	22946	15.01
1976	387206	31864	12.15
1977	439831	44057	9.98

Yellow Perch

The major fishing methods for yellow perch were 2" gill nets, shallow-trap nets, fyke nets, and hoop nets. Shallow-trap nets are the most widely used gear and were selected as the standard gear. The total catch and effort data for Lake Michigan are listed in Table 28.

For yellow perch the parameter values appear to have changed substantially between 1960 and 1977. The estimates for 1960 to 1977 (least

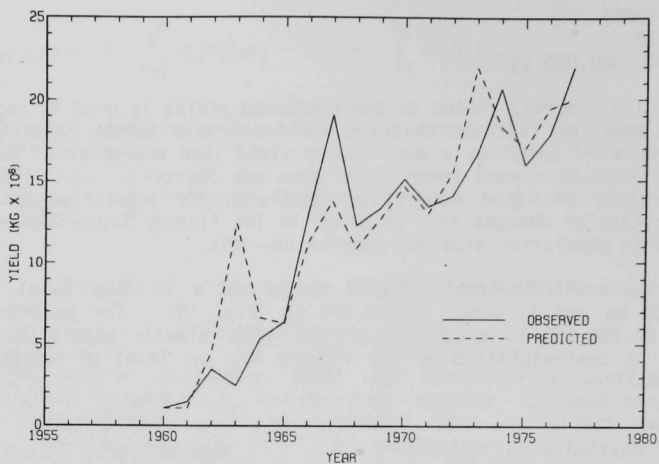


Fig. 18. Observed yields and yields predicted by surplus production model for alewife in Lake Michigan.

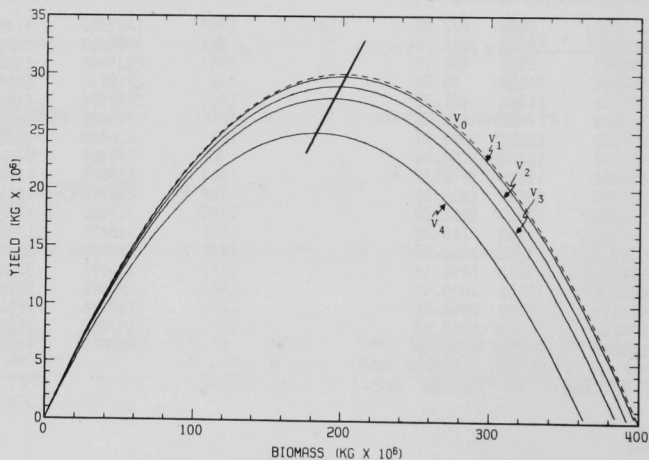


Fig. 19. Stock production curves for alewife in Lake Michigan at 5 different levels of water withdrawal considering only the impact of impingement ($f = 0.1071 \times 10^{-12}$); $V_0 = 0.0 \text{ m}^3/\text{yr}$; $V_1 = 1.0 \times 10^{10} \text{ m}^3/\text{yr}$; $V_2 = 5.0 \times 10^{10} \text{ m}^3/\text{yr}$; $V_3 = 10.0 \times 10^{10} \text{ m}^3/\text{yr}$; $V_4 = 25.0 \times 10^{10} \text{ m}^3/\text{yr}$.

squares) of the population parameters are:

$$k = 0.01$$

$$B_{\infty} = 80,000,000 \text{ kg}$$

$$q = 0.0000001.$$

But these estimates result in a substantial overestimate of recent yields. Better estimates of yield from 1965 to 1977 are obtained with the parameters:

$$k = 0.20$$

$$B_{\infty} = 14,837,363 \text{ kg}$$

$$q = 0.0000014.$$

Observed yields and predicted yields using these parameters appear in Figure 20. It appears that the carrying capacity of Lake Michigan for yellow perch decreased substantially between 1960 and 1977. Yields have decreased from more than 2,500,000 kg to less than 500,000 kg. The model accurately predicts yields from 1965 to 1977. At present the maximum sustainable yield of about 741,869 kg occurs at a biomass of about 7,000,000 kg. A further analysis of the data is necessary to determine the degree to which over-fishing is related to the observed decrease in commercial catch.

Smelt

The major commercial fishing methods for smelt are 1" gill nets and pound nets. Pound nets were selected as the standard gear. The total catch and effort data for smelt in Lake Michigan are listed in Table 29.

Table 29. Total catch (kg), pound net effort (lifts), and catch per unit of effort for smelt in Lake Michigan, 1960-1977.

Year	Catch	Effort	CPUE
1960	1479932	4841	305.66
1961	715538	2620	273.02
1962	702333	2186	321.26
1963	526710	2045	257.47
1964	404620	959	421.91
1965	419599	1124	373.27
1966	503533	1087	462.97
1967	554953	812	683.44
1968	811191	944	859.06
1969	1125453	641	1753.72
1970	923976	482	1914.06
1971	588707	369	1591.14
1972	312880	177	1765.69
1973	393846	336	1171.43
1974	774028	341	2265.82
1975	527318	208	2528.01
1976	983727	303	3237.12
1977	331362	300	1101.38

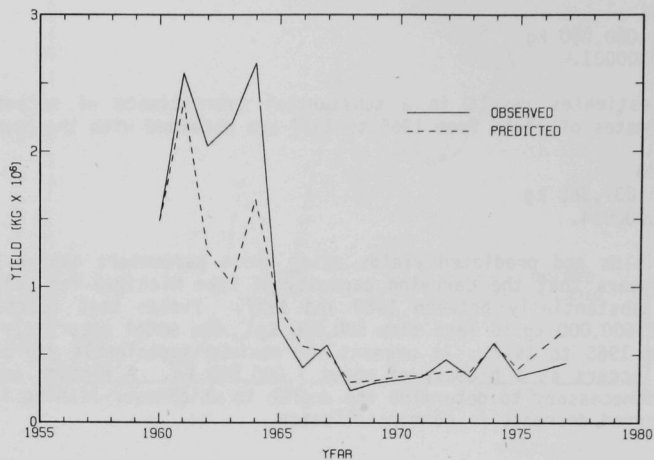


Fig. 20. Observed yields and yields predicted by surplus production model for yellow perch in Lake Michigan.

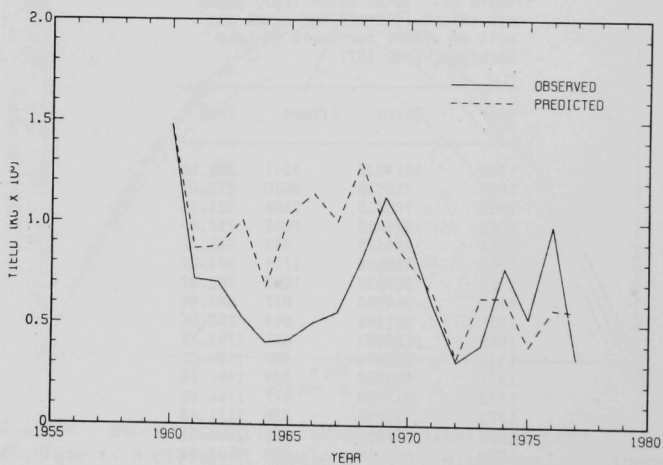


Fig. 21. Observed yields and yields predicted by surplus production model for smelt in Lake Michigan.

For smelt the estimates of the model parameters are:

$$q = 0.0001$$

$$k = 0.50$$

$$B_{\infty} = 20,000,000 \text{ kg.}$$

Again, it is clear that dramatic changes have occurred in abundance (Fig. 21). The model fits well from about 1969 to 1977 but for earlier years the model predicts much higher yields than were observed.

The smelt population in Lake Michigan is not heavily exploited by the commercial fishery. The maximum sustainable yield is 2,500,000 kg and the observed yield has seldom been more than 1,000,000 kg. The size of the smelt population also fluctuated widely between 1960 and 1977. To accurately assess the impact of fishing a more detailed analysis is necessary.

Dynamic Pool Model

Parameter estimates for the dynamic pool model were obtained either directly from the literature or were calculated from data in the literature.

Table 30. Growth of alewife in Lake Michigan. [30]

Age	Length (mm)	Weight (gm)
1	97	7.24
2	142	22.90
3	163	34.67
4	175	42.66
5	183	48.98
6	195	58.88
7	204	67.61

Alewife

The length, weight, and age data for alewife in Table 30 were reported by Brown [30] for female alewife in 1964. The parameters for growth in terms of length were found by fitting the equation

$$l(x + 1) = l_{\infty}(1 - K) + Kl(x)$$

by least squares, where:

$$l(x + 1) = \text{length at age } x + 1 \text{ (in mm).}$$

The estimates of the growth parameters are $K = 0.31$ and $l_{\infty} = 224$. The relation between length and weight for alewife is given by the parabolic equation [30]

$$\log_{10} W = -5.12 + 3.01 \log_{10} \ell$$

and the von Bertalanffy growth equation is

$$W(x) = 0.11642 (1 - e^{-0.31 x})^3$$

where weight is measured in kg. The asymptotic weight is $W_{\infty} = 0.11642$ kg.

To obtain the number of eggs per unit of biomass a relation between length and egg production [31] (Table 31) was applied with estimates of average length (170 mm) and average weight (39.23 g). The number of eggs produced per kg of female was estimated as $EUB = 368,000$ (14,436 eggs per female).

The total mortality rate for alewife (Table 32) was estimated from age structure data reported by Edsall et al. [26]. The total instantaneous mortality rate estimated by least squares is 0.50. Using the estimate of q obtained with the surplus production model and the observed fishing effort, the fishing mortality was estimated as $F = qE = 0.06$. The egg mortality and larval mortality coefficients were obtained by calibration of the observed yield with the calculated yield. The parameter estimates for alewife are listed in Table 33.

Yellow Perch

Much of the biological data for yellow perch in Lake Michigan is summarized by Brazo, Tack, and Liston [32]. From the growth data in Table 34 the growth parameters were estimated as $\ell_{\infty} = 300$ and $K = 0.45$. The length-weight relation used was

$$\log_{10} W = -5.17 + 3.30 \log_{10} \ell$$

which gives the asymptotic weight $W_{\infty} = 1.0$ kg. Length is in millimeters and weight is in grams.

A total mortality coefficient of 0.36 was estimated from the data in Table 35. The number of eggs produced per unit of biomass was calculated from the equation

$$\log_{10} G = -3.712 + 3.451 \log_{10} \ell$$

where ℓ is total length in mm. The average length was taken as 200 mm which gives 17,309 eggs per female on the average and 65,316 eggs per kg of female. The parameter estimates are summarized in Table 36.

Table 31. Fecundity of alewife in Green Bay as a function of length.^[31]

Age	Number	Mean Length	Number Eggs
2	18	160	11147
3	15	176	16138
4	2	192	22407

Table 32. Age structure of alewife in Lake Michigan.^[14]

Age	Relative Number
1	1000
2	600
3	300
4	120
5	36
6	13
7-8	3

Table 33. Estimates of alewife parameters for dynamic pool model.

Parameter	Symbol	Estimate
Asymptotic weight	W_{∞}	0.1164
Average weight	W_{avg}	0.0392
Catchable age	x_c	2.0
Impingeable age	x_i	1.0
Age when length is zero	x_0	0.0
Instantaneous fishing mortality coefficient	F	0.06
Instantaneous natural mortality coefficient	M	0.50
Age at maturity	x_{mat}	2.0
Growth parameter	K	0.30
Eggs per unit biomass	EUB	368,000.0
Egg mortality coefficient	M_1	11.51
Larval mortality coefficient	M_2	5.50
Duration of egg stage	Δt_1	0.10
Duration of larval stage	Δt_2	1.00

Table 34. Standard length (mm) of yellow perch at the end of each year of life.^[32]

Age	Ludington		Green Bay		N.W. Lake	
	♀	♂	♀	♂	♀	♂
2	162	159	99	99	96	
3	206	182	137	130	128	
4	225	215	173	159	154	
5	252	235	197	185	183	
6	291	247	228	211	212	
7	313	252	251	227	-	

Table 35. Age structure of yellow perch population in Lake Michigan at Ludington.^[32]

Age	Relative Number
1	12
2	65
3	619
4	423
5	272
6	138
7	13

Table 36. Estimates of yellow perch parameters for dynamic pool model.

Parameter	Symbol	Estimate
Asymptotic weight	W_{∞}	1.0
Average weight	W_{avg}	0.265
Catchable age	x_c	3.0
Impingeable age	x_I	1.0
Age when length is zero	x_0	0.0
Instantaneous fishing mortality coefficient	F	0.06
Instantaneous natural mortality coefficient	M	0.30
Age at maturity	x_{mat}	2.00
Growth parameter	K	0.45
Eggs per unit biomass	EUB	65316.0
Egg mortality coefficient	M_1	11.51
Larval mortality coefficient	M_2	5.50
Duration of egg stage	Δt_1	0.10
Duration of larval stage	Δt_2	1.00

Smelt

Much of the available information on smelt was published by Bailey [33]. Application of the same methods used for alewife and yellow perch gives the parameter estimates summarized in Table 37.

Table 37. Estimates of smelt parameters for dynamic pool model.

Parameter	Symbol	Estimate
Asymptotic weight	W_{∞}	0.03
Average weight	W_{avg}	0.0140
Catchable age	x_c	2.0
Impingeable age	x_I	1.0
Age when length is zero	x_0	0.0
Instantaneous fishing mortality coefficient	F	0.03
Instantaneous natural mortality coefficient	M	0.40
Age at maturity	x_{mat}	2.00
Growth constant	K	0.56
Eggs per unit biomass	EUB	107337.0
Mortality coefficient for eggs	M_1	11.51
Mortality coefficient for larvae	M_2	5.50
Duration of egg stage	Δt_1	0.10
Duration of larval stage	Δt_2	1.00

ESTIMATION OF POWER PLANT-RELATED PARAMETERS

Surplus Production Model

In the surplus production model impingement at the i^{th} water intake is modeled as:

$$\frac{dI_i}{dt} = f_i Q_i B$$

where:

I_i = number of fish impinged at water intake i at time t

B = population biomass estimated from surplus production model.

The impingement coefficient can be estimated as

$$f_i = \frac{\Delta I_i}{Q_i B}.$$

Annual biomass impinged (ΔI_i) and volume flow (Q_i) were estimated from plant data. The biomass of the population in the lake in 1975 was calculated from the 1975 commercial catch and effort data and the catchability parameter which was estimated from the surplus production model using the equation:

$$B = \frac{1}{q} (1975 \text{ CPUE}).$$

Entrainment of eggs and larvae were modeled as:

$$\frac{dG_i}{dt} = p_i Q_i G$$

and

$$\frac{dL_i}{dt} = h_i Q_i G.$$

Applying the same approach as above for impingement, the following equations can be obtained for the egg and larval entrainment coefficients:

$$p_i = \frac{\Delta G_i}{Q_i G}$$

and

$$h_i = \frac{\Delta L_i}{Q_i L}$$

where:

ΔG_i = number of eggs entrained annually at water intake i

ΔL_i = number of larvae entrained annually at water intake i .

The number of eggs produced by the population was estimated as:

$$G = EUB \frac{B}{2}.$$

The number of larvae produced was calculated using the equation

$$L = (1 - M_1 - \sum_{i=1}^n p_i Q_i) G$$

where M_1 is the natural mortality between the egg and larval stages. In all calculations it was assumed that $M_1 = 0.99$.

Alewife

For alewife the catchability coefficient was estimated as $q = 0.00001$ and the catch per unit of effort in 1975 was 2064. The biomass in the lake in 1975 is estimated as:

$$B = 206,400,000 \text{ kg.}$$

The estimates of the proportion impinged and the impingement coefficients are listed in Table B1. (Appendix B). The proportions of eggs and larvae entrained and the egg and larval entrainment coefficients are listed in Tables B2. and B3., respectively.

Yellow Perch

The least squares estimate of the catchability coefficient for yellow perch is 0.0000001 but this estimate results in overestimates of catches from the late 1960's into the 1970's. A better fit of predicted yields to observed yields for recent years is obtained with $q = 0.0000014$. The catch per unit of effort in 1975 was 15 which gives the 1975 biomass as:

$$B = \frac{1}{0.0000014} \cdot 15 = 10,714,285 \text{ kg.}$$

The estimates of the proportions impinged and the impingement coefficients are listed in Table B4. The proportions of eggs and larvae entrained and the egg and larval entrainment coefficients are listed in Tables B5. and B6., respectively.

Smelt

For smelt in Lake Michigan the catchability coefficient was estimated as $q = 0.0001$ and the catch per unit of effort in 1975 was 2528 giving the 1975 biomass in the lake as

$$B = \frac{1}{0.0001} \cdot 2528 = 25,280,000 \text{ kg.}$$

The estimates of the proportion of smelt impinged and the impingement coefficients are listed in Table B7. The proportions of eggs and larvae entrained and the egg and larval entrainment coefficients are listed in Tables

B8. and B9., respectively.

Dynamic Pool Model

In the dynamic pool model impingement at the i^{th} water intake was modeled as:

$$\frac{dI_i}{dx} = f_i Q_i B(x).$$

The impingement coefficients were estimated as:

$$f_i = \frac{\Delta I_i}{Q_i B}$$

where ΔI_i is the biomass impinged annually at water intake i . Biomass of the population in the lake was estimated using the equation

$$B = RW_{\infty} e^{-M(x_c - x_I)} \sum_{j=0}^3 \frac{U_j e^{-jK(x_c - x_0)}}{F + M + jK}$$

and the number of recruits was estimated as

$$R = \frac{(M + F) C e^{M(x_c - x_I)}}{F}$$

where C is the catch (in numbers) from the fishery.

Entrainment of eggs and larvae was modeled using the equations

$$\frac{dG'}{dx} = p_i Q_i G$$

$$\frac{dL'}{dx} = h_i Q_i L$$

and the entrainment coefficients were estimated as:

$$p_i = \frac{\Delta G_i}{Q_i G}$$

$$h_i = \frac{\Delta L_i}{Q_i L}.$$

The number of eggs produced by the population was estimated as:

$$G = \frac{EUB}{2} \int_{x_m}^{\infty} B(x) dx$$

where x_m is the age at maturity and EUB is the number of eggs produced per unit of biomass.

The number of larvae produced was calculated using the equation

$$L = Ge^{-(M_1 + \sum_{i=1}^n p_i Q_i) \Delta t_1}$$

and the number of recruits produced by these larvae was calculated as

$$R = Ge^{-(M_1 + \sum_{i=1}^n p_i Q_i) \Delta t_1} - (M_2 + \sum_{i=1}^n h_i Q_i) \Delta t_2 .$$

All of the terms in the above equations have been described previously. A summary of the terms can be found in the glossary.

Alewife

The yield of alewife in 1975 was 15,961,428 kg (Table 27) and the number of alewife in the catch was estimated as 406,870,000. The estimate of the biomass of the population in the lake obtained from the parameters listed in Table 33 is 237,401,824 kg. The estimates of the proportions impinged and the impingement coefficients are listed in Table B10. The proportions of eggs and larvae entrained and the egg and larval entrainment coefficients are listed in Tables B11. and B12., respectively.

Yellow Perch

The yield of yellow perch in 1975 was 344,354 kg (Table 28) and the catch was estimated as 1,299,449 perch. The estimate of the biomass of the population in the lake obtained from the parameters listed in Table 36 is 15,339,617 kg. The estimates of the proportions impinged and the impingement coefficients are listed in Table B13. The proportions of eggs and larvae entrained and the egg and larval entrainment coefficients are listed in Table B14. and B15., respectively.

Smelt

The yield in 1975 was 527,318 kg and the number of smelt in the catch was estimated as 37,665,712. The estimate of the biomass of the population in the lake obtained from the parameters listed in Table 37 is 24,697,856 kg. The estimates of the proportions impinged and the impingement coefficients are listed in Table B16. The proportions of eggs and larvae entrained and the egg and larval entrainment coefficients are listed in Tables B17. and B18., respectively.

SIMULATION OF IMPINGEMENT AND ENTRAINMENT IMPACTS

Both the dynamic pool model and the surplus production model were applied to simulate the impact of water withdrawal on the standing stocks and yields to the fishery. The separate results obtained with these two models were similar; therefore, only the results for the surplus production model are reported. The impact of impingement was slightly less with the dynamic pool model because recruitment was assumed to be constant. In addition, the combined impacts of entrainment and impingement are difficult to model with the dynamic pool model. In these respects, the surplus production model is somewhat superior to the dynamic pool model.

Under equilibrium conditions where $dB/dt = 0$, the biomass equation of the surplus production model that includes terms for impingement becomes

$$kB - \frac{k}{B_{\infty}} B^2 - qEB - \sum_{i=1}^n f_i Q_i B = 0$$

and the population biomass as a function of volume flow can be written as

$$B = \frac{B_{\infty}(k - qE)}{k} - \frac{B_{\infty} \bar{f} \sum_{i=1}^n Q_i}{k}$$

where \bar{f} is an average impingement coefficient for the water intakes. This equation predicts a linear decrease in the biomass of the standing stock as the volume flow is increased.

Under equilibrium conditions ($dB/dt = 0$) the equilibrium yield from the population is given by the equation

$$Y_e = kB - \frac{k}{B_{\infty}} B^2 - \sum_{i=1}^n f_i Q_i B.$$

The relation between equilibrium yield and biomass is a parabola. Application of the equation $dY/dt = qEB$ shows that equilibrium yield also is a function of fishing effort, i.e.,

$$Y_e = \frac{B_{\infty} q}{k} (k - \sum_{i=1}^n f_i Q_i) E - \frac{B_{\infty} q^2}{k} E^2.$$

Thus, the relation between equilibrium yield and fishing effort also is a parabola. The maximum sustainable yield, MSY, occurs at a biomass level of $B_{\infty}/2$, and is given by the equation

$$MSY = \frac{kB_{\infty}}{4} - \frac{\bar{f}B_{\infty}}{2} \sum_{i=1}^n Q_i$$

where \bar{f} is the average impingement coefficient. The maximum sustainable yield decreases linearly as the volume flow increases. With zero volume flow the MSY is given by $kB_{\infty}/4$.

Equations similar to those above were applied to simulate the impact of larval and egg entrainment on the size of the standing stock and on the maximum sustainable yield. For entrainment the equations are:

$$B = \frac{B_{\infty}(k - qE)}{k} - \frac{(\bar{p} + \bar{h})B_{\infty}}{k} \sum_{i=1}^n Q_i$$

$$MSY = \frac{kB_{\infty}}{4} - \frac{B_{\infty}(\bar{p} + \bar{h})}{2} \sum_{i=1}^n Q_i$$

where \bar{p} and \bar{h} are the average egg and larval entrainment coefficients. To simulate the combined impact of entrainment and impingement the following two equations were applied:

$$B = \frac{B_{\infty}(k - qE)}{k} - \frac{(\bar{f} + \bar{p} + \bar{h})B_{\infty}}{k} \sum_{i=1}^n Q_i$$

$$MSY = \frac{kB_{\infty}}{4} - \frac{B_{\infty}(\bar{f} + \bar{p} + \bar{h})}{2} \sum_{i=1}^n Q_i$$

Alewife

The impact of water withdrawal appears to be largest on alewife so the results for alewife will be given in greater detail than those for smelt and yellow perch. The equilibrium stock production curve for alewife under five different rates of water withdrawal is shown in Fig. 19. Only the impact of impingement is modeled in this figure. Increasing the volume of withdrawal decreases the carrying capacity, the biomass level at which the maximum sustainable yield occurs, and the maximum sustainable yield. The line drawn through the maxima of the stock production curves is:

$$MSY = \frac{kB_{\infty}}{4} - \frac{\bar{f}B_{\infty}}{2} \sum_{i=1}^n Q_i$$

The total design volume flow of all water intakes on Lake Michigan is about $4.8 \times 10^{10} \text{ m}^3$ per year. This level of flow results in slight decreases in the carrying capacity and MSY. Substantial increases in the volume of flow are necessary to cause a large impact on yield and standing stock. The impacts of entrainment, impingement, and the combined impacts of entrainment and impingement on alewife are summarized in Figs. 22 to 27.

The highest impingement coefficient observed is 0.4331×10^{-12} and the average impingement coefficient is 0.1071×10^{-12} . The relation between standing stock biomass and volume flow for these impingement coefficients are:

$$B = 279,266,660 - 0.0001428Q, \quad \bar{f} = 0.1071 \times 10^{-12}$$

$$B = 279,266,660 - 0.0005775Q, \quad f = 0.4331 \times 10^{-12}.$$

Biomass of the standing stock decreases slowly as the volume withdrawn increases (Fig. 22). At a volume flow of $4.8 \times 10^{10} \text{ m}^3/\text{yr}$ (full capacity flow at all water intakes) the total lakewide impingement (ΔI) of alewife was estimated to be $2.1 \times 10^6 \text{ kg}$ (Table 6). Based on the 1975 biomass estimate of 206,400,000 kg, the proportion of the standing stock impinged ($\Delta I/B_{1975}$) is 0.0102 (or 1.02%). The proportion reduction in the standing stock (Fig. 22) is calculated from the equation:

$$\frac{B_N - B}{B_N} = \frac{(\bar{f} B_{\infty} / k)}{B_N} Q,$$

where B_N = biomass with no water withdrawal. Assuming the average impingement coefficient and a flow of $4.8 \times 10^{10} \text{ m}^3/\text{yr}$, the reduction in standing stock of alewife was 0.0245 (2.45%). The reduction in the standing stock is greater than the proportion of the stock impinged because the surplus production model assumes that the growth rate of the population is a function of population size. Impingement reduces the biomass in the lake until a level is reached where the rate of impingement is balanced by the increased growth rate of the stock.

The impact of impingement on the yield to the fishery also is not large. The relation between the maximum sustainable yield and volume flow is given by the equations:

$$\text{MSY} = 30,000,000 - 0.00002142Q, \quad \bar{f} = 0.1071 \times 10^{-12}$$

$$\text{MSY} = 30,000,000 - 0.00008662Q, \quad f = 0.4331 \times 10^{-12}.$$

The maximum sustainable yield decreases slowly as volume flow increases (Fig. 23). Applying the average impingement coefficient the proportion reduction in maximum sustainable yield is 0.034 (3.4%) at a volume flow of $4.8 \times 10^{10} \text{ m}^3/\text{yr}$. The impact on yield is greater than the impact on standing stock.

The maximum egg and larval entrainment coefficients are 0.1712×10^{-12} and 0.1743×10^{-14} and the average values are 0.1756×10^{-13} and 0.2236×10^{-15} . The relation between biomass of the standing stock and volume flow for entrainment are:

$$B = 279,266,660 - 0.0002306Q, \quad p = 0.1712 \times 10^{-12}, \quad h = 0.1743 \times 10^{-14}$$

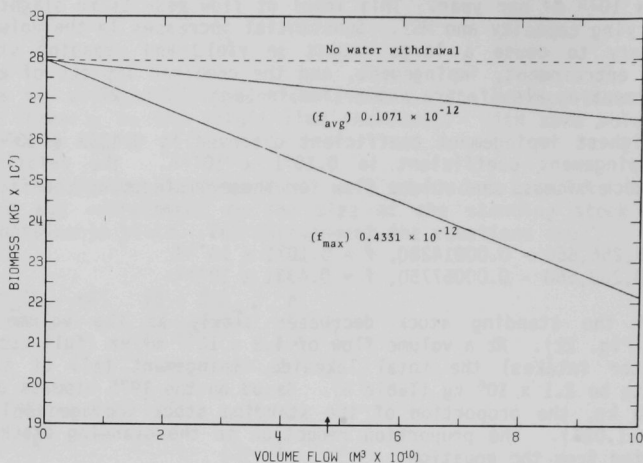


Fig. 22. Impingement impact of increased water withdrawal on biomass of alewife in Lake Michigan (1975). Arrow indicates total design flow for all water intakes in 1975.

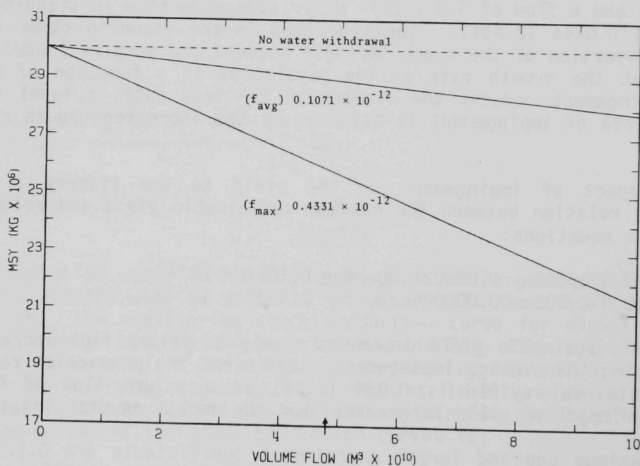


Fig. 23. Impingement impact of increased water withdrawal on maximum sustainable yield (MSY) of alewife in Lake Michigan (1975). Arrow indicates total design flow for all water intakes in 1975.

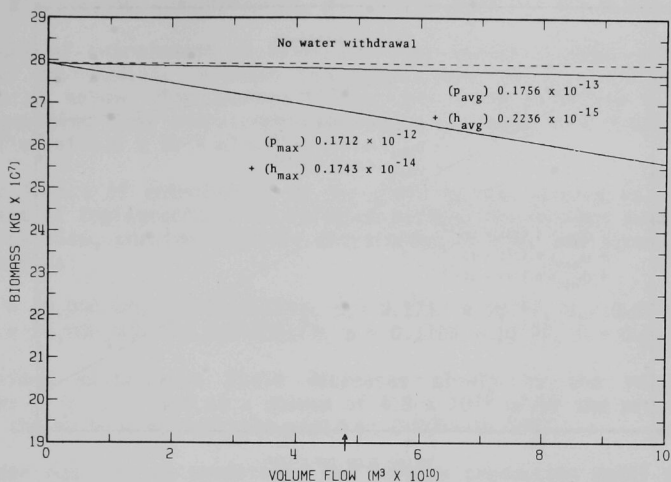


Fig. 24. Entrainment impacts of increased water withdrawal on biomass of alewife in Lake Michigan (1975). Arrow indicates total design flow for all water intakes in 1975.

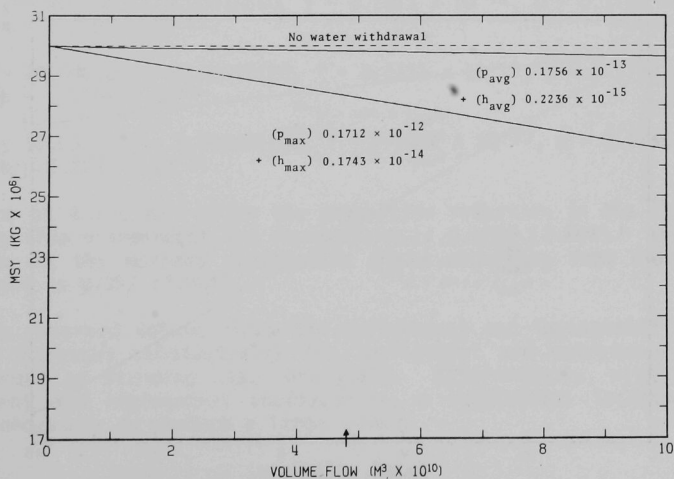


Fig. 25. Entrainment impact of increased water withdrawal on maximum sustainable yield (MSY) of alewife in Lake Michigan (1975). Arrow indicates total design flow for all water intakes in 1975.

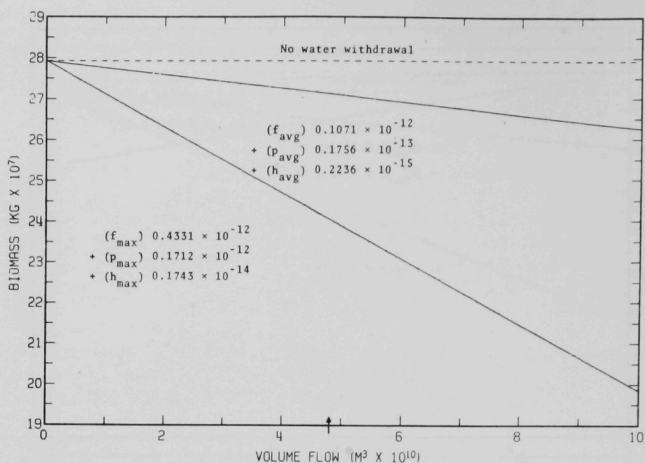


Fig. 26. Combined entrainment and impingement impact of increased water withdrawal on biomass of alewife in Lake Michigan (1975). Arrow indicates total design flow for all water intakes in 1975.

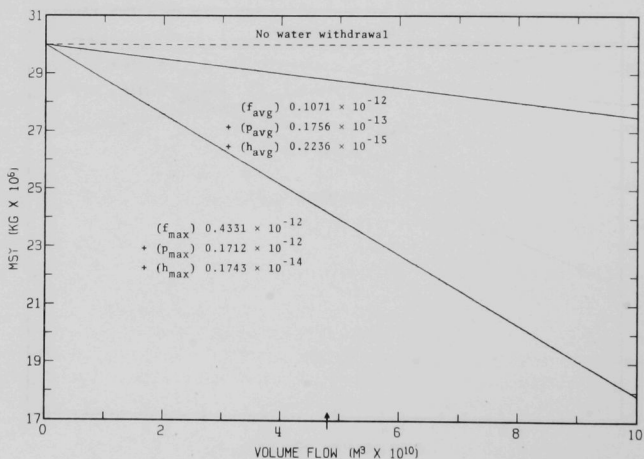


Fig. 27. Combined entrainment and impingement impact of increased water withdrawal on maximum sustainable yield (MSY) of alewife in Lake Michigan (1975). Arrow indicates total flow for all water intakes in 1975.

$$B = 279,266,660 - 0.00002371Q, \bar{p} = 0.1756 \times 10^{-13}, \bar{h} = 0.2236 \times 10^{-15}.$$

The impact of entrainment on biomass of the standing stock is less than the impact of impingement. Biomass decreases slowly due to entrainment of larvae and eggs as volume flow increases (Fig. 24). The reduction in the standing stock resulting from entrainment of larvae and eggs is 0.00407 (0.41%) at a volume flow of $4.8 \times 10^{10} \text{ m}^3/\text{yr}$.

The impact of entrainment on the yield to the fishery is also less than the impact of impingement. The relation between the maximum sustainable yield and volume flow, considering only entrainment of eggs and larvae, is given by the equations:

$$\begin{aligned} \text{MSY} &= 30,000,000 - 0.00003459Q, p_- = 0.1712 \times 10^{-12}, h_- = 0.1743 \times 10^{-14} \\ \text{MSY} &= 30,000,000 - 0.000003557Q, p = 0.1756 \times 10^{-13}, h = 0.2236 \times 10^{-15}. \end{aligned}$$

The maximum sustainable yield decreases slowly as the volume withdrawn increases (Fig. 25), and at a volume of $4.8 \times 10^{10} \text{ m}^3/\text{yr}$ the proportion reduction in the maximum sustainable yield is 0.0056 (0.56%).

Under equilibrium conditions the surplus production model predicts that the impact of entrainment and impingement is additive. The combined impact of entrainment and impingement on the standing stock and the maximum sustainable yield is given by the following equations:

$$B = 279,266,660 - 0.0008081Q, f = 0.4331 \times 10^{-12}, p = 0.1712 \times 10^{-12}, h = 0.1743 \times 10^{-14}.$$

$$B = 279,266,660 - 0.0001665Q, \bar{f} = 0.1071 \times 10^{-12}, \bar{p} = 0.1756 \times 10^{-13}, h = 0.2236 \times 10^{-15}.$$

$$\text{MSY} = 30,000,000 - 0.0001212Q, f = 0.4331 \times 10^{-12}, p = 0.1712 \times 10^{-12}, h = 0.1743 \times 10^{-14}.$$

$$\text{MSY} = 30,000,000 - 0.00002498Q, \bar{f} = 0.1071 \times 10^{-12}, \bar{p} = 0.1756 \times 10^{-13}, h = 0.2236 \times 10^{-15}.$$

At a flow of $4.8 \times 10^{10} \text{ m}^3/\text{yr}$ the proportion reduction in the standing stock resulting from entrainment and impingement is 0.0286 (2.86%). The proportion reduction in the maximum sustainable yield resulting from entrainment and impingement is 0.398 (3.98%).

With observed volume flows the entrainment and impingement coefficients must be increased substantially for impingement and entrainment to have a large impact on standing stock and yield. Alternatively, with the observed entrainment and impingement coefficients, a substantial increase in volume flow is necessary to produce a large impact.

Yellow Perch

The impacts of entrainment and impingement on yellow perch are not as large as the impacts on alewife.

The impingement coefficient for the Pulliam plant (Green Bay) is much

higher than those for intakes on the main body of Lake Michigan, so the average impingement coefficient was calculated using the coefficients for the 15 other sampled intakes.

The average impingement coefficient for yellow perch in Lake Michigan is 0.6705×10^{-14} and the highest impingement coefficient is 0.2962×10^{-13} . The relations between biomass, maximum sustainable yield, and volume flow, considering only impingement are:

$$B = 12,265,439 - 0.0000004974Q, \bar{f} = 0.6705 \times 10^{-14}$$

$$B = 12,265,439 - 0.000002197Q, f = 0.2962 \times 10^{-13}$$

$$MSY = 741,869 - 0.0000004974Q, f = 0.6705 \times 10^{-14}$$

$$MSY = 741,869 - 0.000002197Q, f = 0.2962 \times 10^{-13}$$

The maximum egg and larval entrainment coefficients for yellow perch (excluding Pulliam) are 0.1759×10^{-13} and 0.1431×10^{-15} , respectively. The average egg and larval entrainment coefficients are 0.2942×10^{-14} and 0.3883×10^{-16} , respectively. The relation between biomass of the standing stock and volume flow, considering only entrainment, are:

$$B = 12,265,439 - 0.000001315Q, p_{\bar{e}} = 0.1759 \times 10^{-13}, h_{\bar{e}} = 0.1431 \times 10^{-15}$$

$$B = 12,265,439 - 0.0000002211Q, p = 0.2942 \times 10^{-14}, h = 0.3883 \times 10^{-16}$$

The relation between maximum sustainable yield and volume flow, considering only entrainment, are:

$$MSY = 741,869 - 0.00000002211Q, \bar{p} = 0.2942 \times 10^{-14}, \bar{h} = 0.3883 \times 10^{-16}$$

$$MSY = 741,869 - 0.0000001315Q, p = 0.1759 \times 10^{-13}, h = 0.1431 \times 10^{-15}$$

The combined impact of entrainment and impingement on the standing stock and maximum sustainable yield of yellow perch are given by the equations below:

$$B = 12,265,439 - 0.0000007185Q, \bar{f} = 0.6705 \times 10^{-14}, \bar{p} = 0.2942 \times 10^{-14}, h = 0.3883 \times 10^{-16}$$

$$B = 12,265,439 - 0.000003513Q, f = 0.2962 \times 10^{-13}, p = 0.1759 \times 10^{-13}, h = 0.1431 \times 10^{-15}$$

$$MSY = 741,869 - 0.0000007185Q, \bar{f} = 0.6705 \times 10^{-14}, \bar{p} = 0.2942 \times 10^{-14}, h = 0.3883 \times 10^{-16}$$

$$MSY = 741,869 - 0.0000003513Q, f = 0.2962 \times 10^{-13}, p = 0.1759 \times 10^{-13}, h = 0.1431 \times 10^{-15}$$

As the volume flow increases, biomass of the standing stock (Fig. 28) and the maximum sustainable yield (Fig. 29) decrease slowly. Assuming the capacity withdrawal of $4.8 \times 10^{10} \text{ m}^3$ and the average entrainment and impingement coefficients, the proportion reduction in standing stock of yellow perch is 0.0028 (0.28%) and the proportion reduction in maximum sustainable yield is 0.0047 (0.47%).

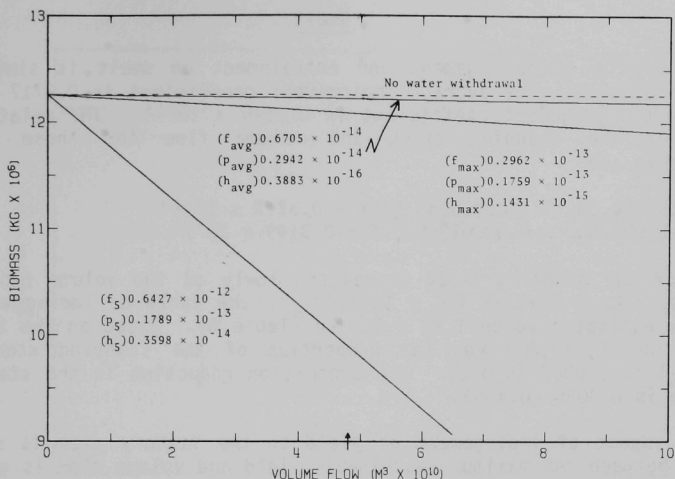


Fig. 28. Combined impingement and entrainment impact of increased water withdrawal on biomass of yellow perch in Lake Michigan. Average and maximum coefficients have been calculated from all sampled power plants except Pulliam. [5] Arrow indicates total design flow for all water intakes in 1975.

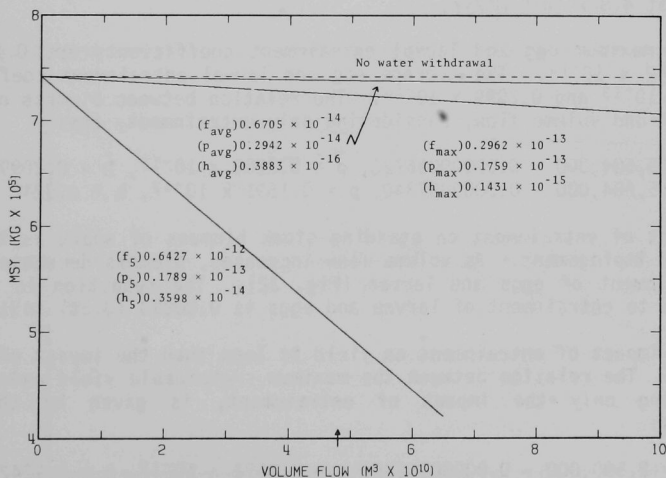


Fig. 29. Combined impingement and entrainment impact of increased water withdrawal on maximum sustainable yield (MSY) of yellow perch in Lake Michigan. Average and maximum coefficients have been calculated from all sampled power plants except Pulliam. [5] Arrow indicates total design flow for all water intakes in 1975.

Smelt

The impact of impingement and entrainment on smelt is similar to the impact on alewife. The average impingement coefficient is 0.3717×10^{-13} and the highest impingement coefficient is 0.3149×10^{-12} . The relation between biomass of the standing stock and volume flow for these impingement coefficients are:

$$B = 15,604,000 - 0.000001487Q, \bar{f} = 0.3717 \times 10^{-13}$$

$$B = 15,604,000 - 0.00001259Q, f = 0.3149 \times 10^{-12}.$$

Biomass of the standing stock decreases slowly as the volume flow withdrawn increases. At a flow of 4.8×10^{10} m³/yr, the lakewide impingement (ΔI) of smelt was estimated to be 1.86×10^4 kg (Table 6). Based on the 1975 biomass estimate of 25,280,000 kg, the proportion of the standing stock impinged ($\Delta I/B_{1975}$) is 0.0007 (0.07%). The proportion reduction in the standing stock (Fig. 30) is 0.0046 (0.46%).

The impact of impingement on yield to the fishery also is small. The relation between the maximum sustainable yield and volume flow is given by the equations:

$$MSY = 2,500,000 - 0.0000003717Q, \bar{f} = 0.3717 \times 10^{-13}$$

$$MSY = 2,500,000 - 0.000003149Q, f = 0.3149 \times 10^{-12}.$$

The maximum sustainable yield decreases slowly as the volume flow increases (Fig. 31). The proportion reduction in yield due to impingement is 0.0071 (0.71%) at 4.8×10^{10} m³/yr.

The maximum egg and larval entrainment coefficients are 0.1519×10^{-12} and 0.9242×10^{-14} . The average egg and larval entrainment coefficients are 0.2208×10^{-13} and 0.2099×10^{-14} . The relation between biomass of the standing stock and volume flow, considering only entrainment, are:

$$B = 15,604,000 - 0.0000009672Q, \bar{p} = 0.2208 \times 10^{-13}, \bar{h} = 0.2099 \times 10^{-14}$$

$$B = 15,604,000 - 0.000006734Q, p = 0.1591 \times 10^{-12}, h = 0.9242 \times 10^{-14}.$$

The impact of entrainment on standing stock biomass of smelt is less than the impact of impingement. As volume flow increases, biomass decreased slowly due to entrainment of eggs and larvae (Fig. 32). The reduction in the standing stock due to entrainment of larvae and eggs is 0.00298 (0.3%) in 1975.

The impact of entrainment on yield is less than the impact of impingement on yield. The relation between the maximum sustainable yield and volume flow, considering only the impact of entrainment, is given by the following equations:

$$MSY = 2,500,000 - 0.000001683Q, p = 0.1591 \times 10^{-12}, h = 0.9242 \times 10^{-14}$$

$$MSY = 2,500,000 - 0.0000002418Q, p = 0.2208 \times 10^{-13}, h = 0.2099 \times 10^{-14}.$$

The maximum sustainable yield decreases slowly as volume flow withdrawn increases (Fig. 33). The proportion reduction in yield due to entrainment is 0.0046 (0.46%) in 1975.

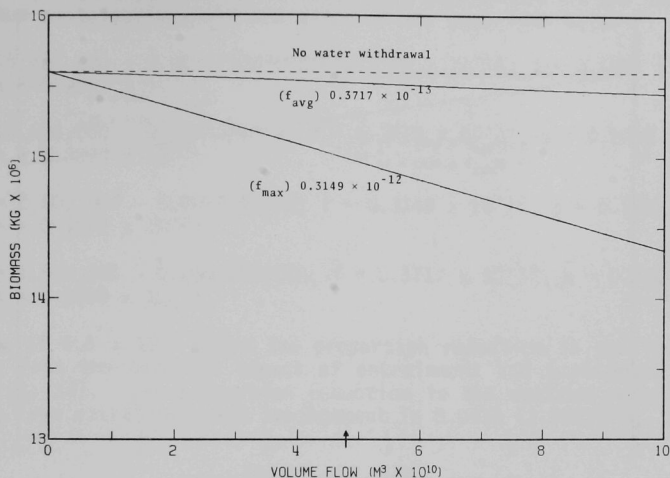


Fig. 30. Impingement impact of increased water withdrawal on biomass of smelt in Lake Michigan (1975). Arrow indicates total design flow for all water intakes in 1975.

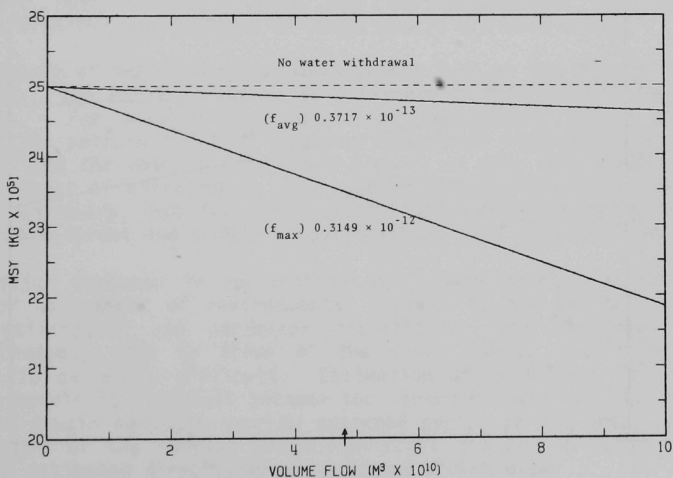


Fig. 31. Impingement impact of increased water withdrawal on maximum sustainable yield (MSY) of smelt in Lake Michigan (1975). Arrow indicates total design flow for all water intakes in 1975.

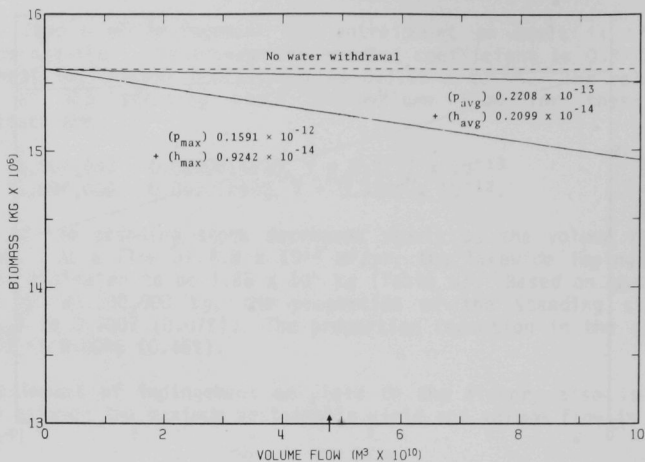


Fig. 32. Entrainment impact of increased water withdrawal on biomass of smelt in Lake Michigan (1975). Arrow indicates total design flow for all water intakes in 1975.

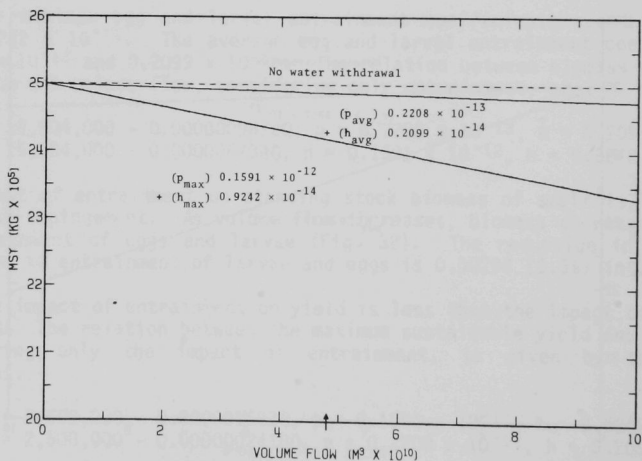


Fig. 33. Entrainment impact of increased water withdrawal on maximum sustainable yield (MSY) of smelt in Lake Michigan (1975). Arrow indicates total design flow for all water intakes in 1975.

The combined impact of entrainment and impingement on the standing stock and maximum sustainable yield are given by the equations below:

$$B = 15,604,000 - 0.00001934Q, \quad f = 0.3149 \times 10^{-12}, \quad p = 0.1591 \times 10^{-12}, \\ h = 0.9242 \times 10^{-14}$$

$$\bar{B} = 15,604,000 - 0.000002454Q, \quad \bar{f} = 0.3717 \times 10^{-13}, \quad \bar{p} = 0.2208 \times 10^{-13}, \\ \bar{h} = 0.2099 \times 10^{-14}$$

$$MSY = 2,500,000 - 0.000004832Q, \quad f = 0.3149 \times 10^{-12}, \quad p = 0.1591 \times 10^{-12}, \\ h = 0.9242 \times 10^{-14}$$

$$\bar{MSY} = 2,500,000 - 0.0000006135Q, \quad \bar{f} = 0.3717 \times 10^{-13}, \quad \bar{p} = 0.2208 \times 10^{-13}, \\ \bar{h} = 0.2099 \times 10^{-14}.$$

At a flow of $4.8 \times 10^{10} \text{ m}^3/\text{yr}$ the proportion reduction in the standing stock resulting from the combined impact of entrainment and impingement is 0.00755 (0.76%)(Fig. 34). The proportion reduction in the maximum sustainable yield resulting from entrainment and impingement is 0.0118 (1.18%)(Fig. 35).

DISCUSSION OF MODELING RESULTS

Direct estimation of the biomass of a fish stock is difficult and assessment of the impact of entrainment and impingement cannot be made without a model that describes the response of the population to these impacts. Fishery models can be applied for estimation of stock biomass and also can be applied for environmental impact assessment after only slight modifications. Fishery models have been widely applied and the assumptions and difficulties associated with the applications of these models are well known.

The impact of impingement can be assessed just as the impact of a fishery is assessed. The model for yield to a fishery is identical to the model for impingement. For alewife the pattern of impingement during the year is similar to the pattern of catch from the commercial fishery (Table 38). Both the fishery and the power plants catch alewife as they move toward shore. To model the impact of entrainment, more substantial modification of the fishery models is necessary, but the modifications are straightforward and in this study the most direct and simplest modifications have been applied.

The major weakness in application of fishery models, as well as other models, for assessment of environmental impacts is the shortage of data for stock identification and parameter estimation. For fisheries undergoing dramatic changes, such as those of the Great Lakes, meaningful parameter estimation is extremely difficult. Estimation of parameters for the surplus production models is difficult because the parameters are not well defined and they do not remain constant over an extended period on the Great Lakes. Both the parameters of the surplus production model are few in number and all of them can be estimated directly from catch and effort data.

Using the available data and varying parameter values resulted in similar fits of the model to the observed catch and effort data (Table 39). For example, increasing k from 0.30 to 0.35 and decreasing B_{∞} from 400,000,000 to 300,000,000 for alewife increases the residual sum of squares by only a small

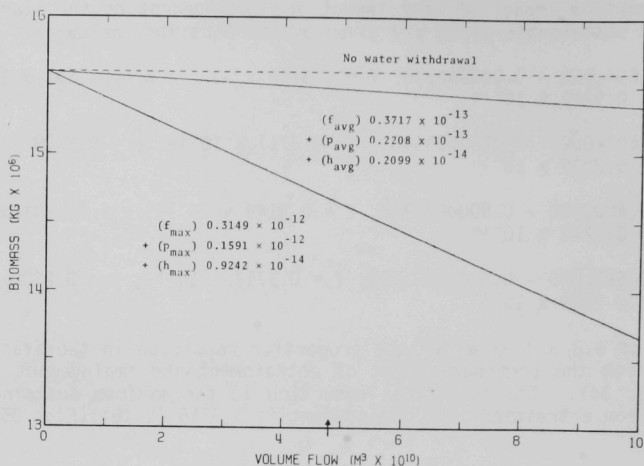


Fig. 34. Combined entrainment and impingement impact of increased water withdrawal on biomass of smelt in Lake Michigan (1975). Arrow indicates total design flow for all water intakes in 1975.

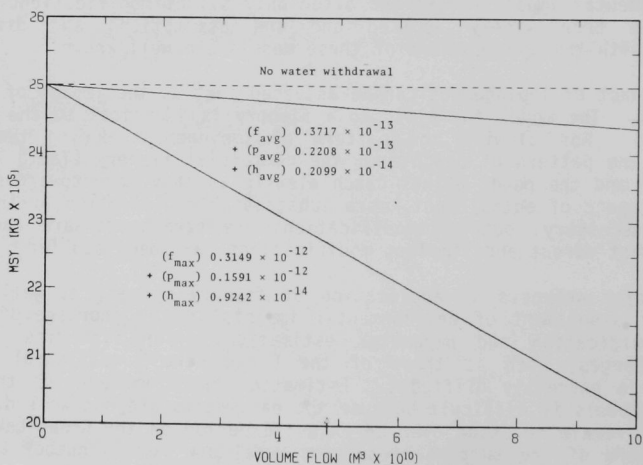


Fig. 35. Combined entrainment and impingement impact of increased water withdrawal on maximum sustainable yield (MSY) of smelt in Lake Michigan (1975). Arrow indicates total design flow for all water intakes in 1975.

amount. Although the fit of the model to the observed data is good, the individual parameter estimates might not be of similar accuracy.

Table 38. Comparison of commercial alewife catch from district WML in Green Bay and observed impingement at Pulliam Power Plant during 1975.

Month	Commercial Catch (kg)	Observed Impingement (kg)
January	0	0
February	9	0
March	13	0
April	78	0
May	79,655	267
June	2,813,451	13,375
July	2,152,849	7,195
August	978,809	3,383
September	564,083	166
October	66,441	86
November	2	79
December	0	6

Table 39. Residual sum of squares for fit of surplus production model to alewife catch and effort data.

Q	0.000005	0.000010	0.000020
<u>Sum of squares for K = 0.25</u>			
B_{\max}			
0.30000000E+09	0.71559846E+15	0.49805058E+15	0.13285475E+16
0.40000000E+09	0.43346152E+15	0.32332165E+15	0.12343199E+16
0.50000000E+09	0.27269751E+15	0.24085464E+15	0.11733996E+16
<u>Sum of squares for K = 0.30</u>			
B_{\max}			
0.30000000E+09	0.58970330E+15	0.25229185E+15	0.70890663E+15
0.40000000E+09	0.32373584E+15	0.18022458E+15	0.58793512E+15
0.50000000E+09	0.22241908E+15	0.26774588E+15	0.52183262E+15
<u>Sum of squares for K = 0.35</u>			
B_{\max}			
0.30000000E+09	0.52456825E+15	0.19093856E+15	0.31439214E+15
0.40000000E+09	0.30174615E+15	0.34051601E+15	0.31592491E+15
0.50000000E+09	0.28995566E+15	0.76056059E+15	0.41336671E+15

To apply the surplus production model for assessment of the impact of entrainment, the production of eggs and survival of eggs and larvae must be estimated. Survival of eggs and larvae was determined from estimates of the number of eggs produced and the assumption that the population was in equilibrium. The sensitivity of the estimates of impact to changes in survival of eggs and larvae should be investigated.

The parameter estimates for the dynamic pool model are based on entirely different kinds of data than those of the surplus production model. The growth parameters and total mortality coefficients were estimated from age structure and growth data available in the literature. Age at maturity and age at recruitment into the fishery also were obtained from the literature. The fishing mortality coefficient, F , was estimated from the surplus production model parameters as $F = qE$. This is the only connection between the two models. The larval and egg mortality parameters were adjusted under the assumption that the stocks were in equilibrium.

In a study such as this where a mathematical model is applied to assess an impact, there is no direct method to determine whether or not the result is reasonable. Therefore, the applications of the dynamic pool and surplus production models were kept as independent as possible so a comparison of the results obtained by the two models could be used as a basis for evaluating the reliability of the estimates of impact. First, the surplus production model was applied. Then, the dynamic pool model was applied using the value of F estimated from the surplus production model. All other parameter estimates are independent. The close agreement between the results obtained with the two models gives some degree of confidence in the results.

Although the results of the two models agree, there might be substantial errors in the estimation of the population parameters in both the surplus production and the dynamic pool models. These errors could produce an error in estimation of biomass which would affect the estimate of impact. However, even a substantial error in the estimate of biomass did not result in a meaningful change in the level of impact on Green Bay. The relation between the estimate of the proportion impinged and the biomass of yellow perch in Green Bay is shown in Fig. 36. A large increase in the estimate of population biomass decreases the level of impact only slightly. The decrease in the estimate of biomass produces a larger change than an increase but decreasing the biomass estimate by one-half only increases the proportion impinged from less than 0.001 to 0.0015. Because the level of impact is small, large errors of estimation do not change the level of impact substantially.

The U.S. Fish and Wildlife Service estimated the adult alewife population vulnerable to bottom trawling to be from 86,000,000 to 131,600,000 kg in 1975 [24]. Using the fishery data and the population models we estimated the alewife biomass in 1975 to be 206,400,000 kg. Although our estimate is nearly twice as large as the estimate made by the Fish and Wildlife Service, it is probably an underestimate of the total alewife biomass in Lake Michigan. The commercial fishery for alewife is not lakewide and unless there is complete mixing of the alewife population, the estimates obtained with the surplus production model should be low.

The 1975 rainbow smelt biomass in Lake Michigan was estimated to be 13,700,000 kg by the U.S. Fish and Wildlife Service [27]. The biomass of

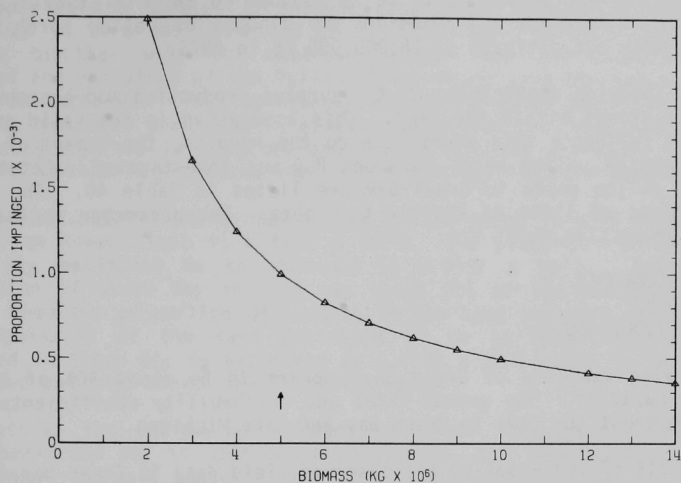


Fig. 36. Relation between estimate of population biomass and estimate or proportion of biomass standing stock impinged for yellow perch in Green Bay (1975). Arrow indicates estimated biomass in 1975.

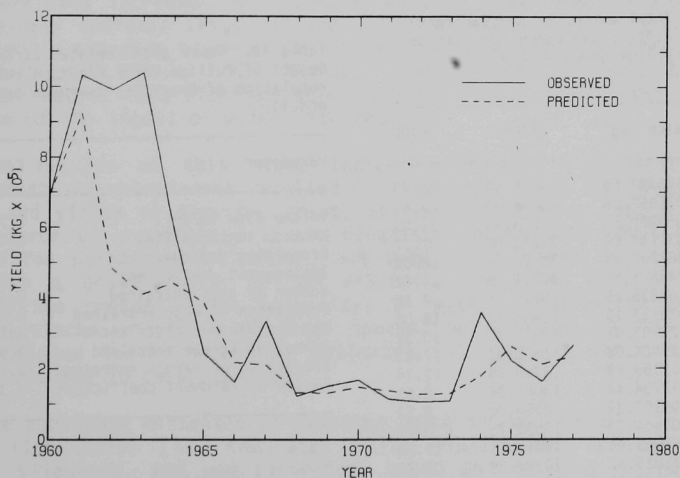


Fig. 37. Observed and predicted yields for yellow perch in Green Bay (1960-1977).

smelt in 1975 was estimated to be 25,280,000 kg in this study. There do not appear to be lakewide estimates of the biomass of yellow perch that can be compared with our estimate of 15,000,000 kg in 1975.

The lakewide application of the surplus production model assumes complete mixing of stocks within the lake. This assumption is not valid and to determine what influence this might have on the results, the impact of the Pulliam Power Plant on yellow perch in Green Bay was investigated. Catch and effort data for yellow perch in Green Bay are listed in Table 40. The effort data are in terms of lifts of shallow trap nets. The parameter estimates for the surplus production model are:

$$\begin{aligned}q &= 0.0000015 \\k &= 0.20 \\B_{\infty} &= 7,000,000 \text{ kg}\end{aligned}$$

The carrying capacity of Green Bay appears to be about 50% of the lakewide carrying capacity. The growth rates and catchability coefficients for yellow perch are about the same in Green Bay and Lake Michigan.

The fit of the model to the observed yield data in Green Bay (Fig. 37) is similar to the lakewide fit (Fig. 20). In Green Bay, as in the rest of Lake Michigan, a large decrease in catch occurred between 1963 and 1965. The model does not accurately predict catches prior to 1965 but predicts catches well from 1965 to 1977. It would appear that the decrease in catch is not related to overfishing. The stock production curve for Green Bay indicates that the yellow perch population is not over-exploited by the commercial fishery. The MSY of 350,000 kg occurs at a biomass of about 3,500,000 kg.

Table 40. Total catch, trap net effort (number of lifts), and catch per unit of effort for yellow perch in Green Bay, 1960-1977.

Year	Catch (kg)	Effort	CPUE
1960	695387.63	29096.64	23.90
1961	1031650.56	43686.96	23.61
1962	989950.88	28273.39	35.01
1963	1039157.50	27513.02	37.77
1964	602275.00	33451.54	18.00
1965	243885.56	32024.59	7.62
1966	161835.25	18713.91	8.65
1967	333137.19	18483.43	18.02
1968	121793.81	11811.77	10.31
1969	149966.06	11871.31	12.63
1970	167150.69	13769.38	12.14
1971	112734.44	13087.94	8.61
1972	105107.39	12353.30	8.51
1973	107444.19	12583.75	8.54
1974	358055.94	18059.01	19.83
1975	221815.31	28387.89	7.81
1976	163233.44	23854.13	6.84
1977	265166.50	26083.35	10.17

Table 41. Power plant-related parameters for impact of Pulliam Power Plant on yellow perch population of Green Bay (surplus production model).

Parameter	Estimate
Volume flow (m ³ /yr)	0.774×10^9
Biomass impinged (kg)	0.4979×10^4
Proportion impinged	0.9957×10^{-3}
Impingement coefficient	0.6427×10^{-12}
Number of eggs entrained	0.4526×10^7
Proportion of eggs entrained	0.2772×10^{-4}
Egg entrainment coefficient	0.1789×10^{-13}
Number of larvae entrained	0.9102×10^6
Proportion of larvae entrained	0.5574×10^{-3}
Larvae entrainment coefficient	0.3598×10^{-14}

Applying the surplus production model, the biomass of yellow perch in Green Bay in 1975 was estimated as 5,206,666 kg. Applying this estimate of biomass together with the observed volume flow and numbers and biomass impinged and entrained at the Pulliam Power Plant gave the parameter estimates listed in Table 41. The impingement and entrainment coefficients are higher when the impact on Green Bay is assessed than when the impact on Lake Michigan is assessed. This is expected because the biomass available to the Pulliam plant is considerably reduced when only Green Bay is under consideration.

The estimate of the proportion of yellow perch in Lake Michigan impinged at Pulliam Power Plant is 0.4978×10^{-3} . The proportion of the biomass in Green Bay estimated to be impinged is 0.9957×10^{-3} . The yellow perch population of Green Bay in 1975 was about 50% of the lakewide estimate for 1975. From the proportion of biomass in the lake impinged and the percent of the population of the lake estimated to be in Green Bay the proportion impinged in Green Bay is estimated as 0.4979×10^{-3} which is identical to the estimated obtained using only Green Bay data.

Because the yellow perch entrainment and impingement coefficients are high when Green Bay is considered separately, the impacts of entrainment and impingement increase substantially as volume flow is increased. The relation between yellow perch standing stock biomass, maximum sustainable yield, and volume flow are given by the equations:

$$B = 5,824,315 - 0.00004648Q$$

$$MSY = 350,000 - 0.000004648Q, f_5 = 0.1285 \times 10^{-11}, p_5 = 0.3578 \times 10^{-13}, h_5 = 0.7195 \times 10^{-14}.$$

As volume flow increases the standing stock biomass and maximum sustainable yield slowly decrease (Figs. 38 and 39). At a flow of $7.74 \times 10^8 \text{ m}^3/\text{yr}$, the reduction in standing stock of yellow perch in Green Bay is 0.0061 (0.61%) and the reduction in MSY is 0.0103 (1.03%). Consideration of Green Bay separately from the rest of Lake Michigan does not result in a significant change in the estimate of the impact of water withdrawal.

The results of this study indicate that the cumulative impacts of impingement and entrainment resulted in relatively small decreases in standing stocks and yields of alewife, smelt, and yellow perch in Lake Michigan. The major source of uncertainty in the results reported here comes from the lack of data for parameter estimation, but even large errors in estimation would not cause a great change in the estimated level of impacts during 1975. Although the present level (capacity) of water withdrawal does not reduce standing stocks or yields of these species by more than a few percent, the intake-related losses should be evaluated in light of the recent status of each population in Lake Michigan.

The published estimates of standing stock biomass of alewife available to trawls (1967-1978) [24] indicate cyclic fluctuations between 40 and 120 million kilograms, and our estimates, based on the fishery indicate a peak biomass of $>206 \times 10^6 \text{ kg}$ in 1975. Recent estimates of the annual consumption of alewife by salmonid predators in Lake Michigan [34] indicate a maximum of 30% of the standing stock biomass was consumed in 1975, a peak year in the cycle of alewife biomass fluctuations, and a maximum of 100% in 1977, a year

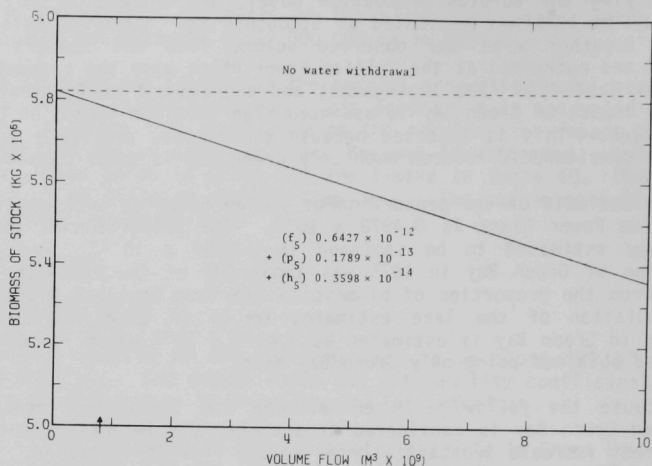


Fig. 38. Combined entrainment and impingement impact of increased water withdrawal on biomass of yellow perch in Green Bay. Arrow indicates total design flow for all water intakes on Green Bay in 1975.

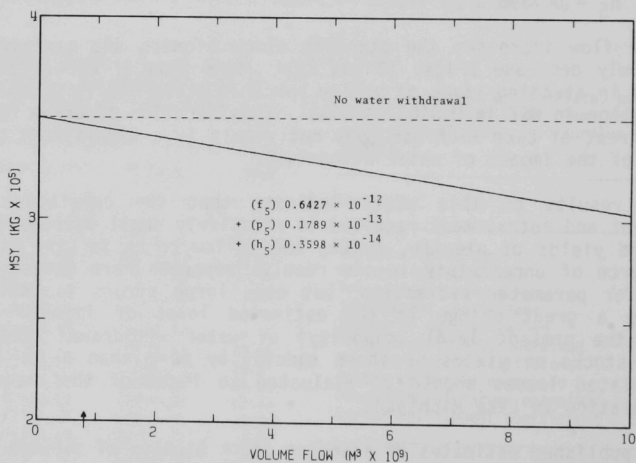


Fig. 39. Combined entrainment and impingement impact of increased water withdrawal of maximum sustainable yield (MSY) of yellow perch in Green Bay. Arrow indicates total design flow for all water intakes on Green Bay 1975.

when estimated alewife biomass was extremely low. Under natural conditions, the numbers of predatory fishes are a direct function of reproductive success, natural mortality rates, and food supply. However, the numbers of salmonids in Lake Michigan are primarily under human control. Social pressures to increase salmonid stocking in Lake Michigan have resulted in the stocking of ~12 million salmonids annually since 1973 and projected stocking rates of 15 million per year by 1985. The potential effects of overstocking salmonids and overcropping alewife are becoming serious issues. The focus of fish management and research efforts must be directed toward forage fish management via allocation of forage production among trophic, commercial, and other interests. For example, the loss of alewife biomass due to commercial fishing in 1975 was approximately 16×10^6 kg. Assuming a limitation on available forage, this biomass would have produced $\sim 2 \times 10^6$ kg of salmonids (assuming a forage to predator conversion ratio of 7:1). Similarly, the loss of alewife to water intakes ($\sim 2 \times 10^6$ kg in 1975) would convert to ~280 thousand kilograms of salmonids.

Estimates of the minimum standing stock biomass of rainbow smelt in Lake Michigan indicate fluctuations between 11 and 16 million kg between 1973 and 1978 [27] and $\sim 25 \times 10^6$ kg in 1975 (this report). Although salmonid predation on smelt is not well quantified, it was recently estimated as $\sim 5.0 \times 10^6$ kg or 20% of the 1975 standing stock biomass [34]. Commercial fishing in 1975 harvested 0.5×10^6 kg (2%) and sport fishing accounted for $\sim 1.3 \times 10^6$ kg (5.2%). The reductions in standing stock of rainbow smelt due to water intakes was estimated to be 0.75%. The status of the rainbow smelt population seems to be partially related to the status of the alewife population and the level of predation by salmonids. Although the smelt population has played a secondary role in the trophic system of Lake Michigan in the past, it may become a more valuable forage base if the alewife population is depleted to the point of being unable to support the predatory pressure.

Yellow perch are not a forage species for salmonids. The yellow perch population in Lake Michigan has fluctuated greatly since 1960. Apparently, the standing stock of yellow perch was $\sim 10.7 \times 10^6$ kg lakewide and 5.2×10^6 kg in Green Bay in 1975. Neither population seems to be impacted by the combined mortalities due to fishing and water intakes.

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GLOSSARY OF TERMS

- Impingement:** entrapment of fishes by water intakes and their subsequent removal from the process stream by traveling screens.
- Entrainment:** entrapment of eggs and immature fishes by water intakes and their passage through the traveling screens into the process stream.
- Ichthyoplankton:** "free-floating" or planktonic fish life-stages. Eggs and larvae are included in this term.
- Traveling Screen:** typically a 3/8" wire-mesh screen located upstream of the intake pumps as a final filter.
- a,b:** parameters in the parabolic length-weight equation.
- B:** biomass of the population at time t .
- B_{∞} :** environmental carrying capacity in terms of biomass (population size without fishing or water withdrawal).
- $B(x)$:** biomass of individuals of age x .
- B_0 :** population biomass at some initial time t .
- C:** annual catch from the fishery in numbers or kg.
- CPUE:** catch per unit effort in the fishery.
- D:** density of fish in lake (kg).
- D_i :** density of fish at i^{th} intake (kg).
- E:** fishing effort in some standard units such as lifts of pound nets or trap nets.
- EUB:** egg production per unit of female biomass.
- f_i :** annual impingement coefficient for water intake i .
- f_{avg} :** average annual impingement coefficient for sampled water intakes.
- f_{max} :** maximum annual impingement coefficient for sampled water intakes.
- F:** instantaneous fishing mortality coefficient.
- G:** number of eggs produced by the population during a period of one year, or the number at time t .
- G'_i :** number of eggs entrained at intake i at time t .
- ΔG_i :** number of eggs entrained at water intake i during one year.
- $G(0)$:** the initial number of eggs produced by a cohort.

h_{avg} : average annual larval entrainment coefficient for sampled intakes.
 h_{max} : maximum annual larval entrainment coefficient for sampled intakes.
 h_i : larval entrainment coefficient for water intake i .
 I : number or biomass of fish impinged at time t .
 ΔI_i : number or biomass of fish impinged at water intake i during one year.
 k : population growth constant in surplus production model.
 K : growth parameter for weight of individual fish.
 l : length of an individual fish.
 l_{∞} : asymptotic length of an individual fish.
 $l(x)$: length of an individual at age x .
 L : number of larvae at time t or at age x .
 L' : number of larvae entrained at time t .
 ΔL_i : number of larvae entrained at water intake i during a period of one year.
 $L(0)$: initial number of larvae produced by a cohort.
 M : instantaneous natural mortality coefficient.
 M_i : mortality resulting from impingement (assumed to = 1).
 M_1 : mortality rate of egg stage.
 M_2 : mortality rate of larvae.
 MSY : maximum sustainable yield.
 n : number of water intakes.
 $N(x)$: number of individuals of age x .
 P_{avg} : average annual egg entrainment coefficient for sampled intakes.
 p_i : egg entrainment coefficient for water intake i .
 P_{max} : maximum annual egg entrainment coefficient for sampled intakes.
 q : catchability coefficient for the commercial fishery.
 Q_i : annual volume flow in m^3 at water intake i .
 R : number of recruits entering exploited population.

t : time in years.

Δt_1 : amount of time from spawning to absorption of yolk sac.

Δt_2 : amount of time from absorption of yolk sac to young-of-year stage.

U_j : integration constants for the dynamic pool model.

V : volume of lake.

W_∞ : asymptotic individual weight for the dynamic pool model.

$W(x)$: weight of an individual at age x .

x : age.

x_c : age when fish became catchable by commercial fishery.

x_r : age when fish re recruited.

x_I : age when fish become impingeable.

x_m : age at maturity.

x_0 : theoretical age when length is zero.

Y_a : annual yield from the commercial fishery.

Y : yield from the commercial fishery at time t .

Y_e : equilibrium yield from fishery.

ϕ : mortality rate for prerecruit life-stages in surplus production model.

APPENDIX A

DAILY IMPINGEMENT AND ENTRAINMENT DENSITIES

Figs. A.1.a - A.16.i: Daily densities of each species/life stage at each sampled plant

Figs. A.1.a-A.16.a: Impinged alewife.

Figs. A.1.b-A.16.b: Impinged smelt.

Figs. A.1.c-A.16.c: Impinged yellow perch.

Figs. A.1.d-A.16.d: Entrained alewife eggs.

Figs. A.1.e-A.16.e: Entrained alewife larvae.

Figs. A.1.f-A.16.f: Entrained smelt eggs.

Figs. A.1.g-A.16.g: Entrained smelt larvae.

Figs. A.2.h-A.16.h: Entrained yellow perch eggs.

Figs. A.2.i-A.16.i: Entrained yellow perch larvae.

NOTE: Figures for plants not reporting a species group were excluded.
Heavy solid lines on x-axis indicate values < appropriate y-axis value.

Figure A. 1.o ZION/ALEWIFE

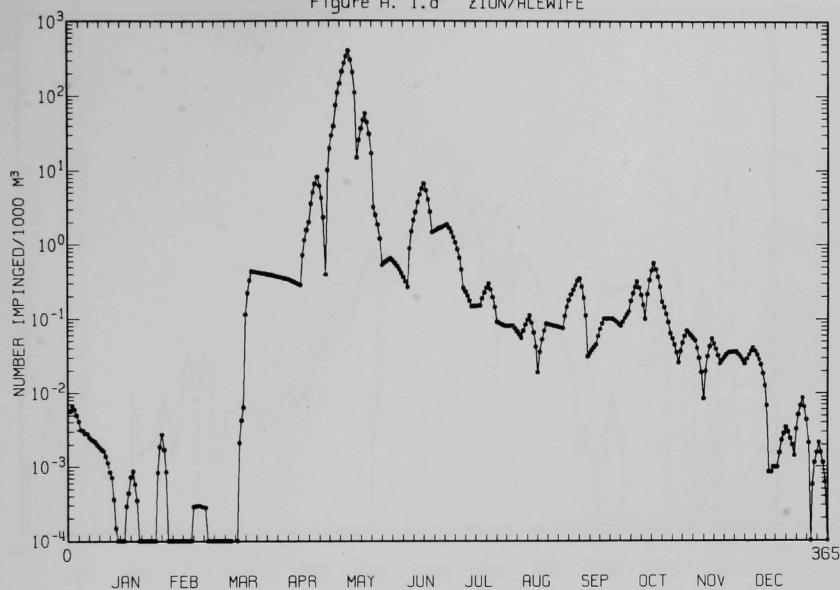
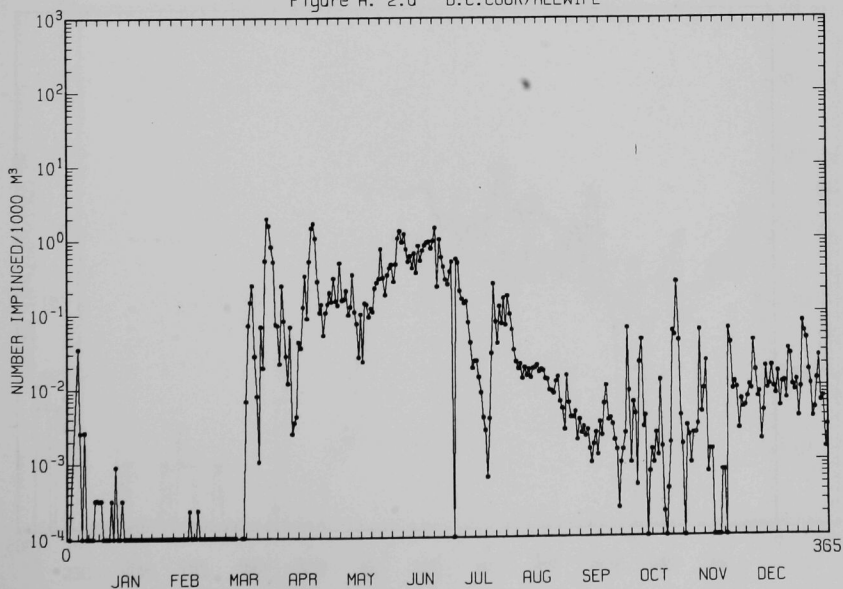


Figure A. 2.o D.C.COOK/ALEWIFE



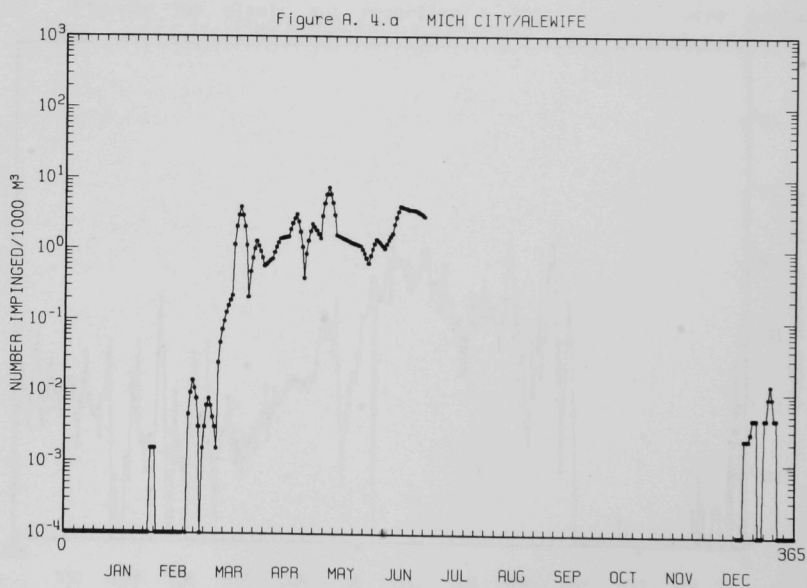
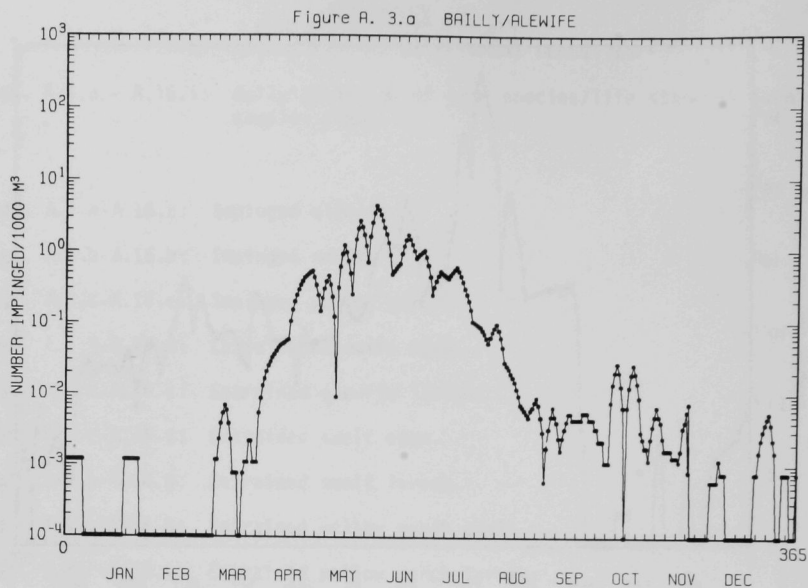


Figure A. 5.a PULLIAM/ALEWIFE

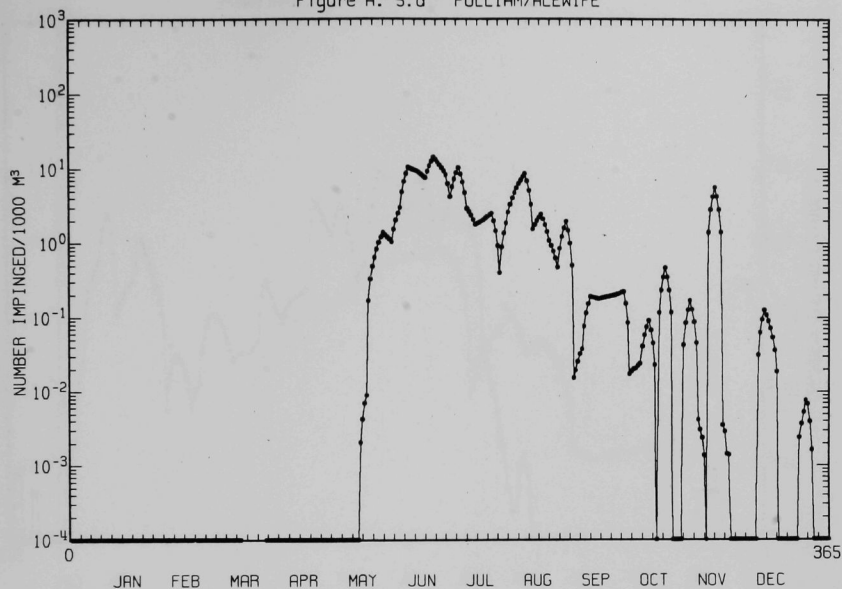
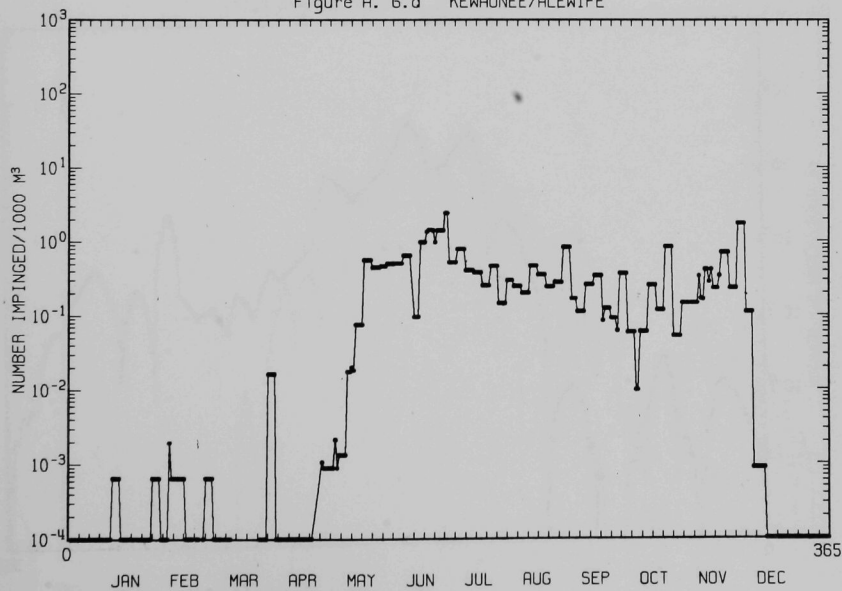


Figure A. 6.a KEWAUNEE/ALEWIFE



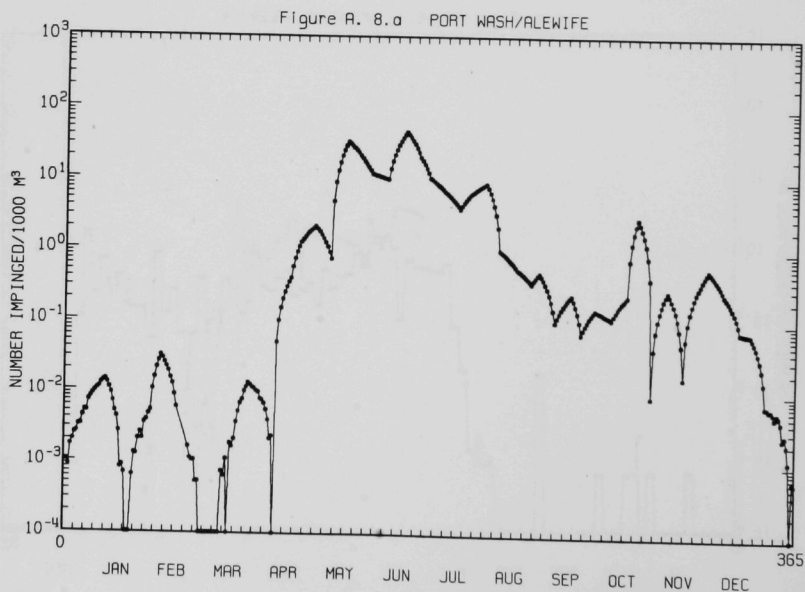
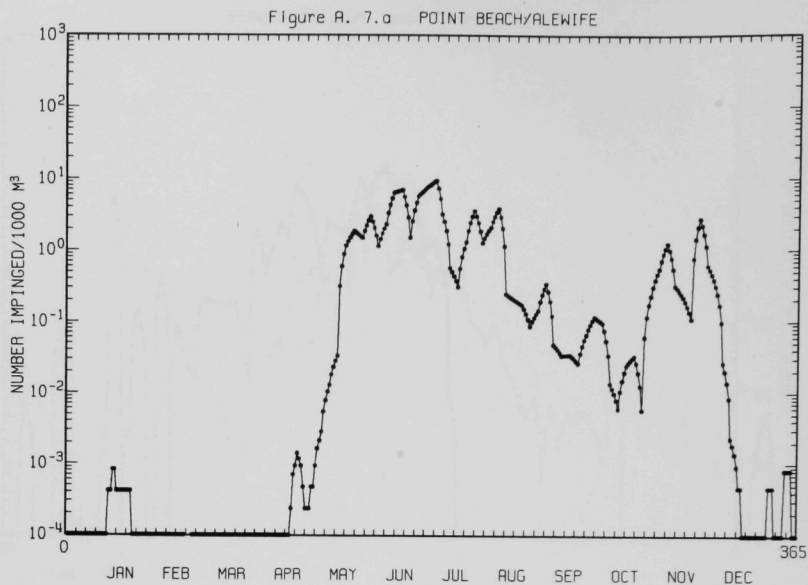


Figure A. 9.a LAKESIDE/ALEWIFE

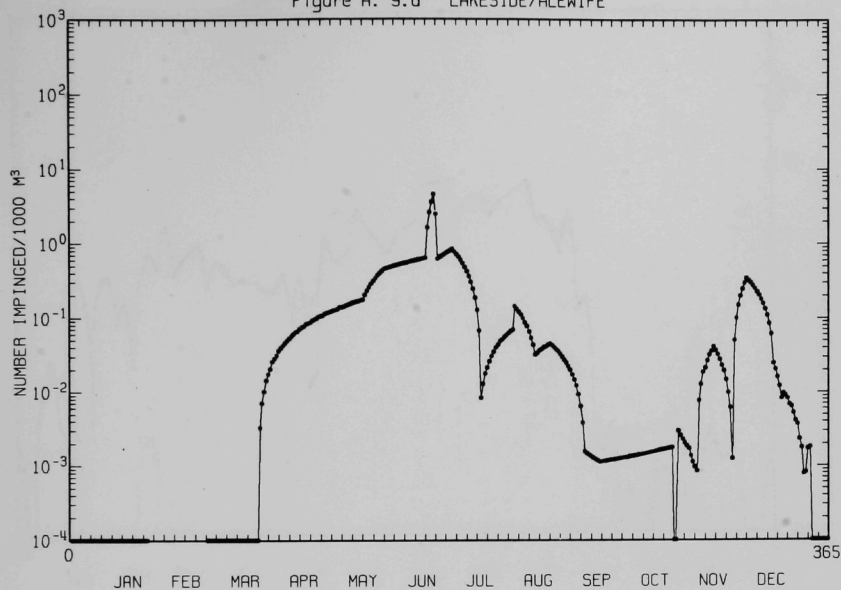
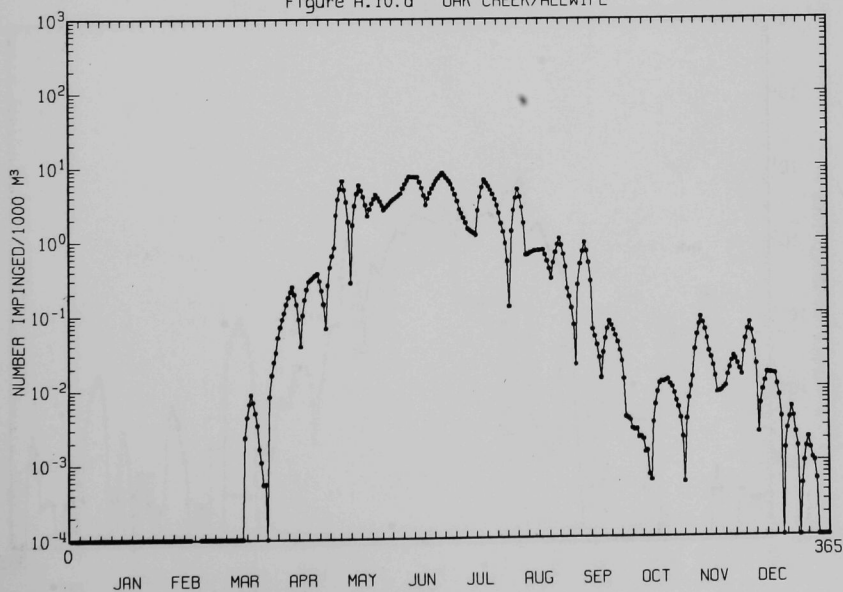


Figure A.10.a OAK CREEK/ALEWIFE



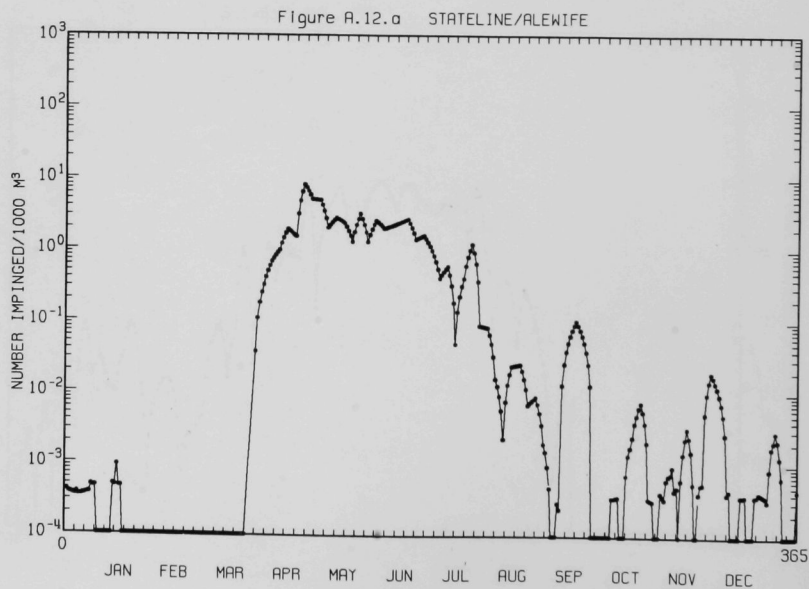
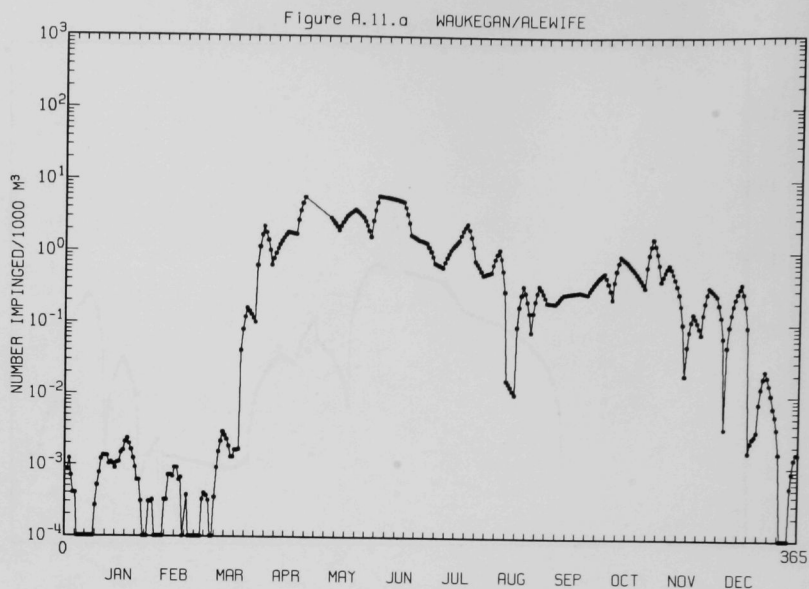


Figure A.13.a MITCHELL/ALEWIFE

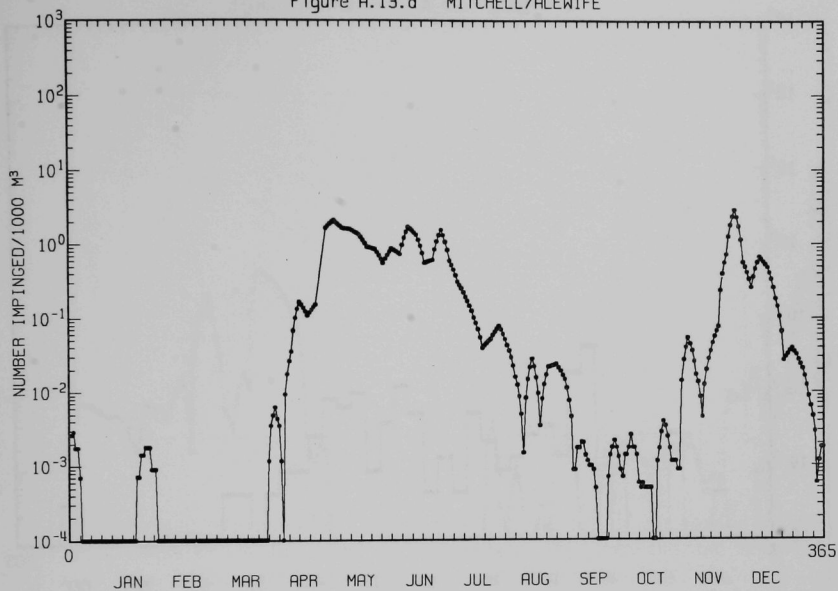
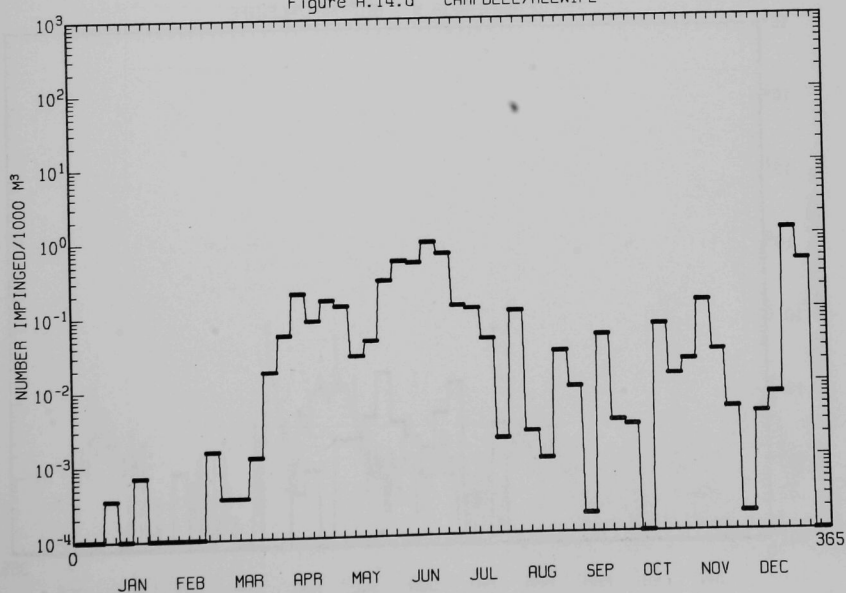


Figure A.14.a CAMPBELL/ALEWIFE



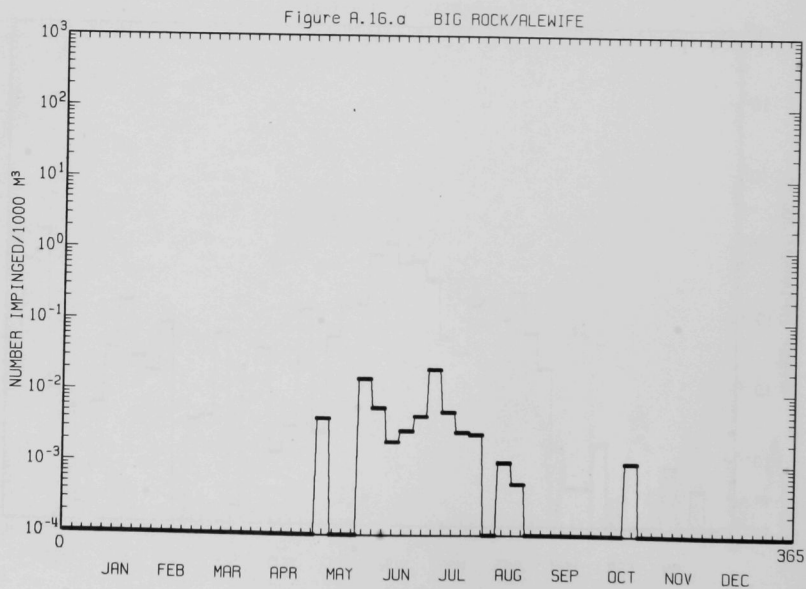
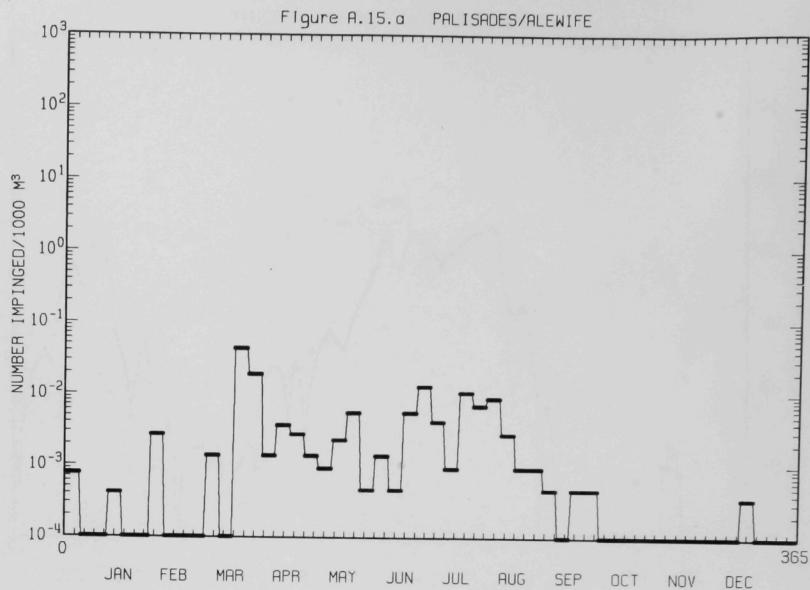


Figure A. 1.b ZION/SMELT

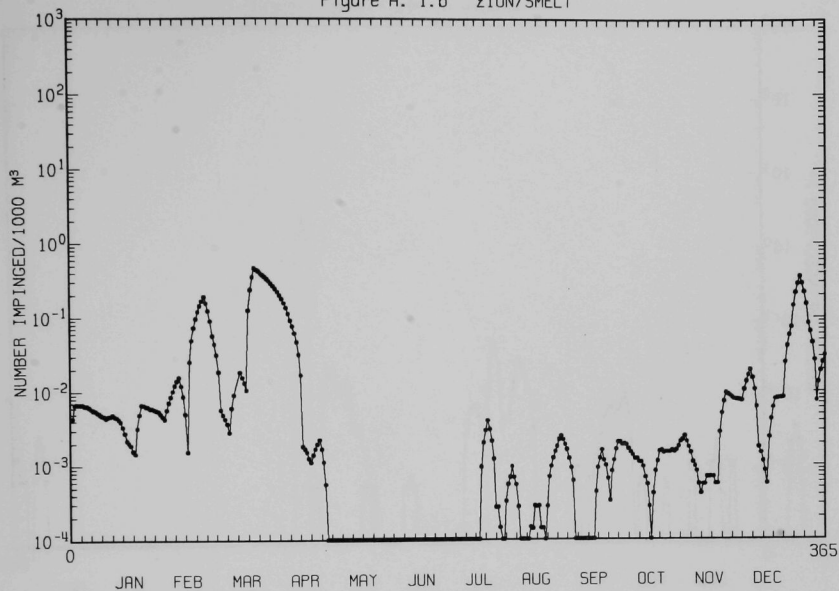


Figure A. 2.b D.C.COOK/SMELT

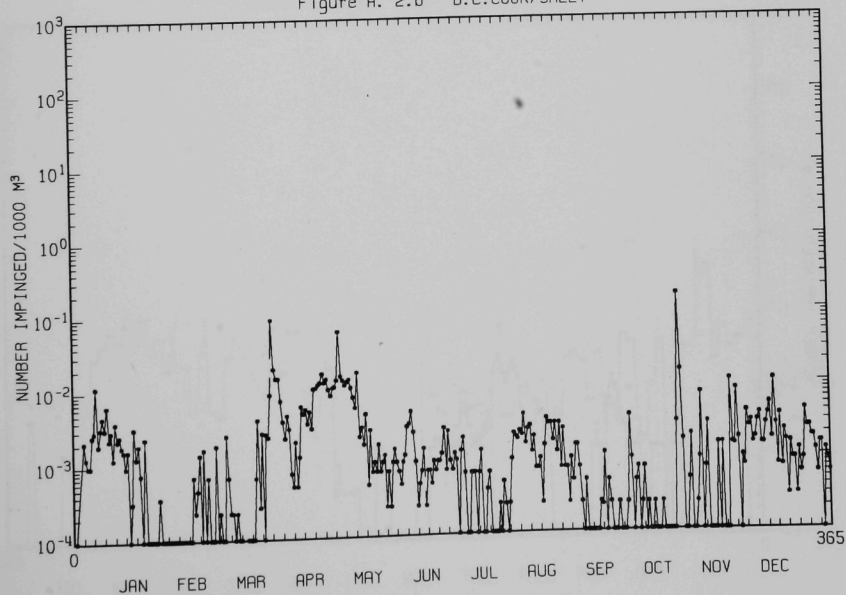


Figure A. 3.b BAILLY/SMELT

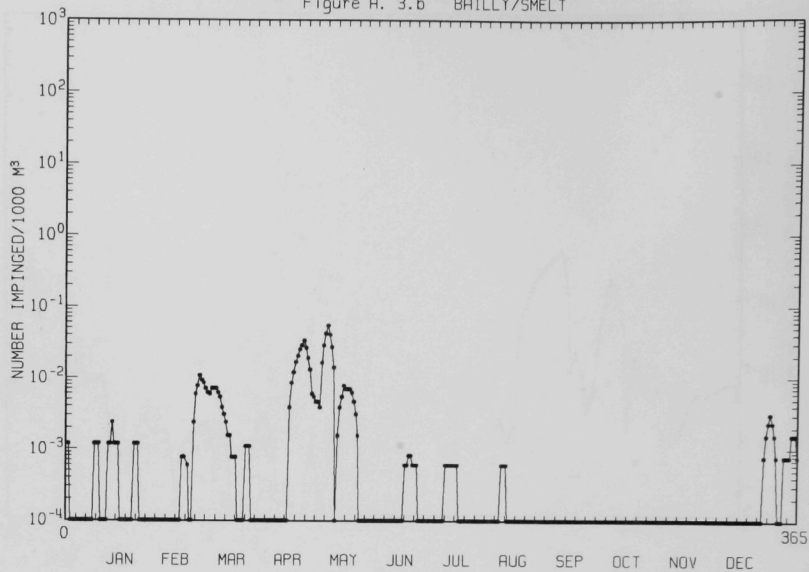


Figure A. 4.b MICH CITY/SMELT

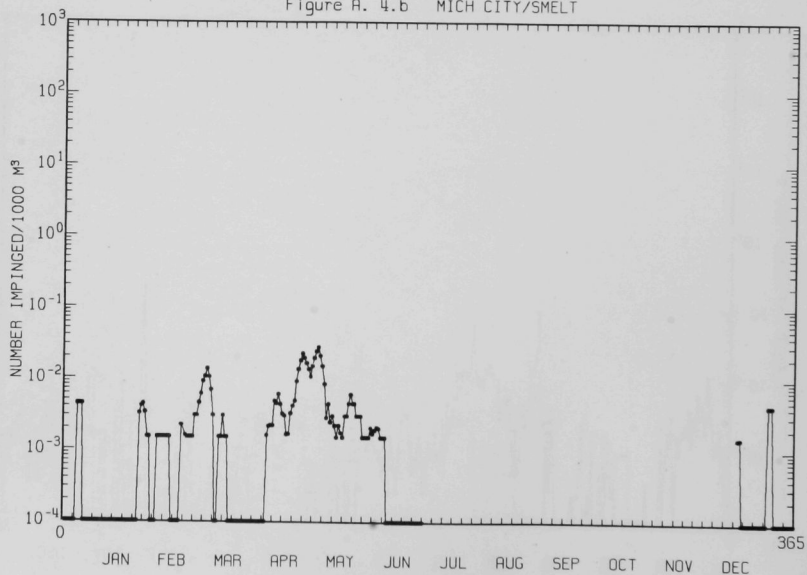


Figure A. 5.b PULLIAM/SMELT

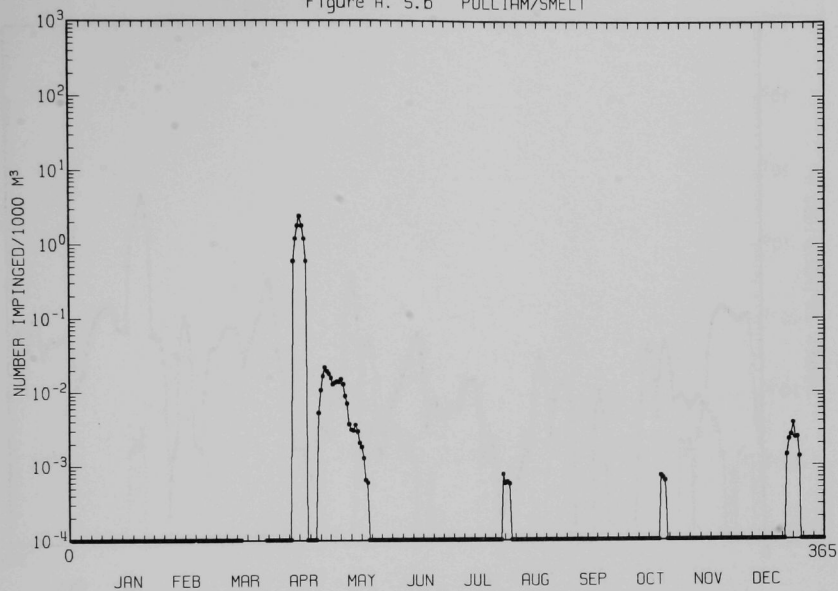


Figure A. 6.b KEWAUNEE/SMELT

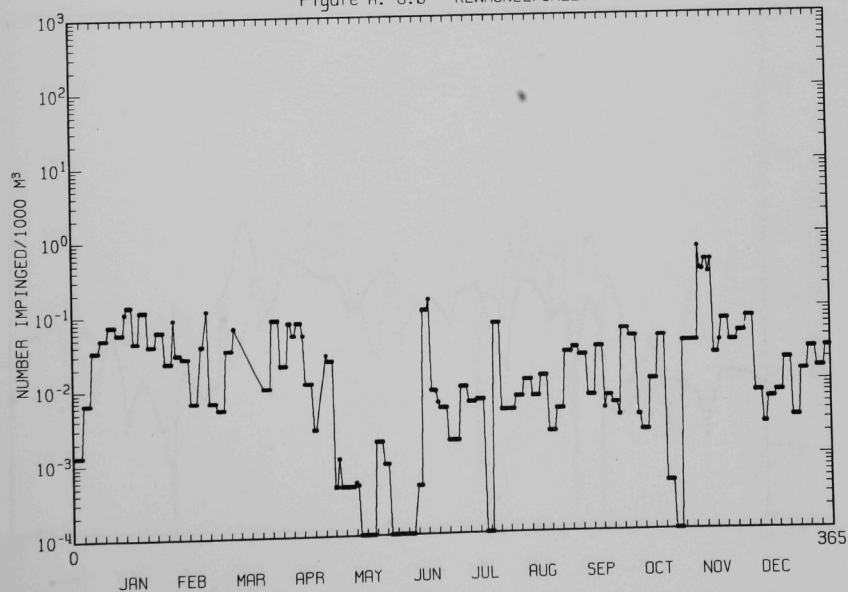


Figure A. 7.b POINT BEACH/SMELT

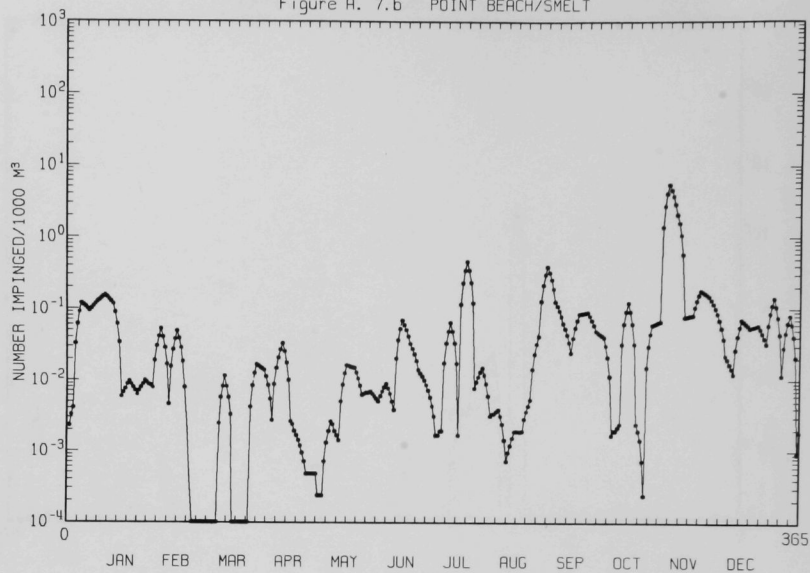


Figure A. 8.b PORT WASH/SMELT

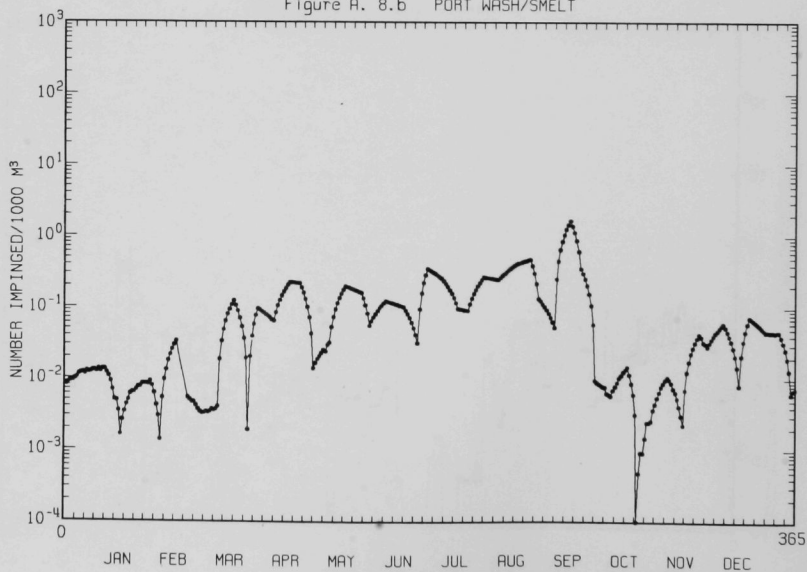


Figure A. 9.b LAKESIDE/SMELT

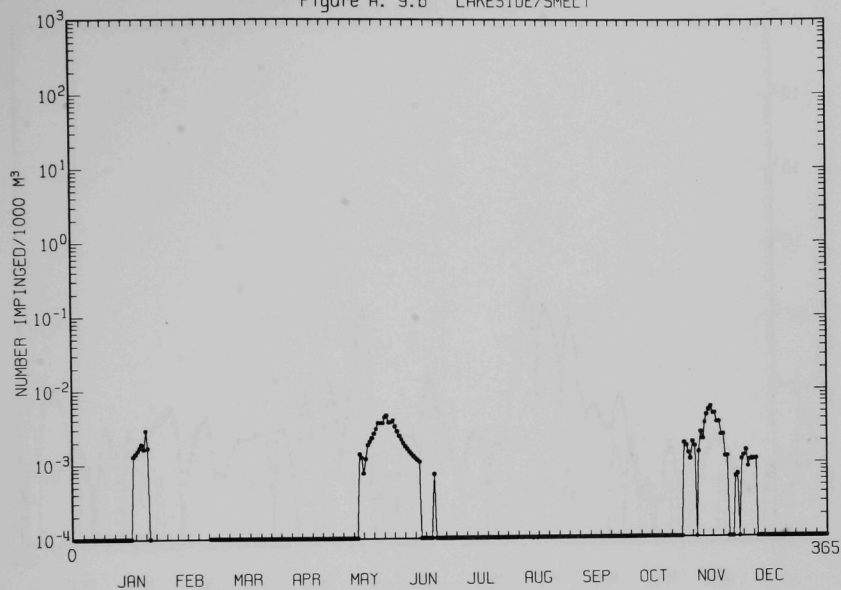


Figure A.10.b OAK CREEK/SMELT

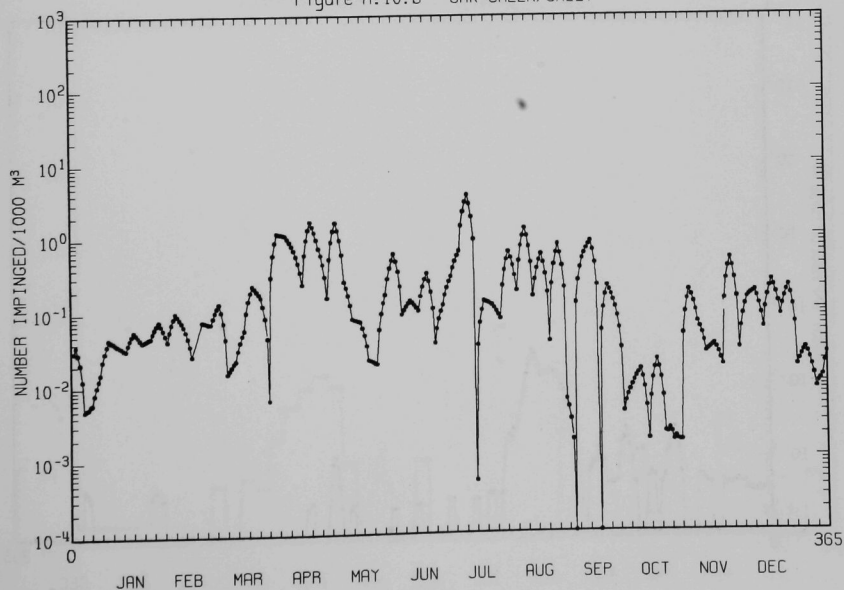


Figure A.11.b WAUKEGAN/SMELT

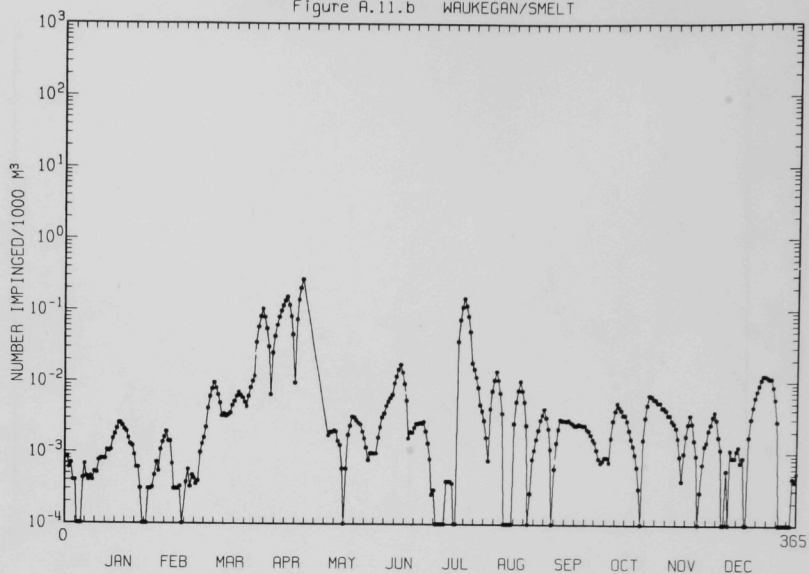


Figure A.12.b STATELINE/SMELT

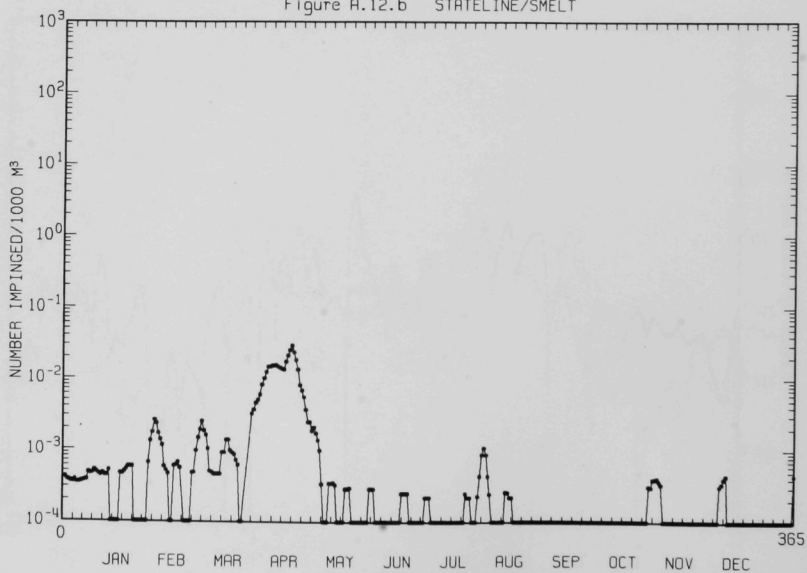


Figure A.13.b MITCHELL/SMELT

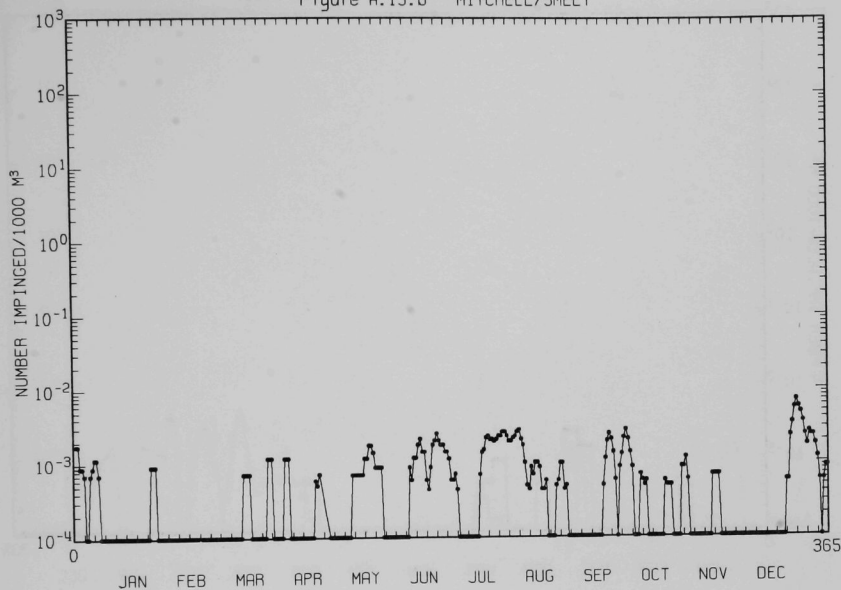


Figure A.14.b CAMPBELL/SMELT

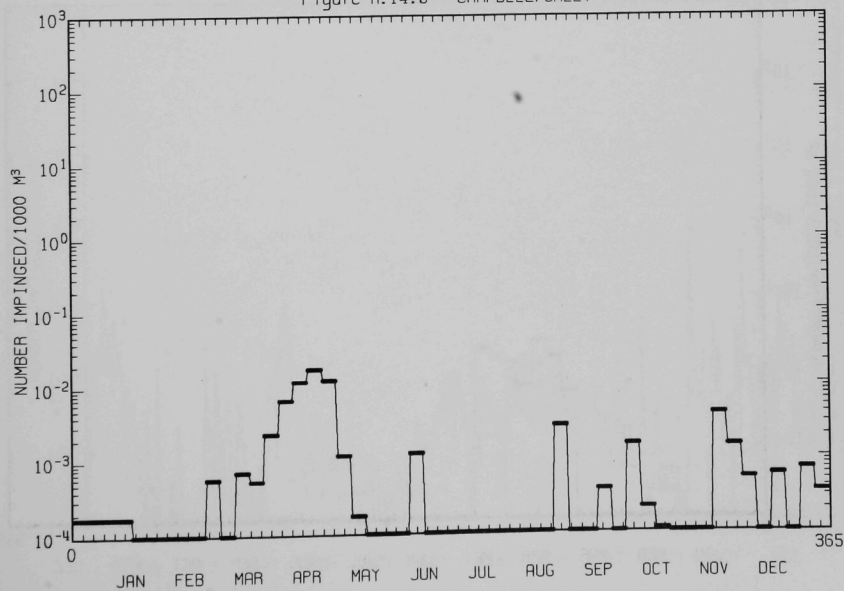


Figure A.15.b PALISADES/SMELT

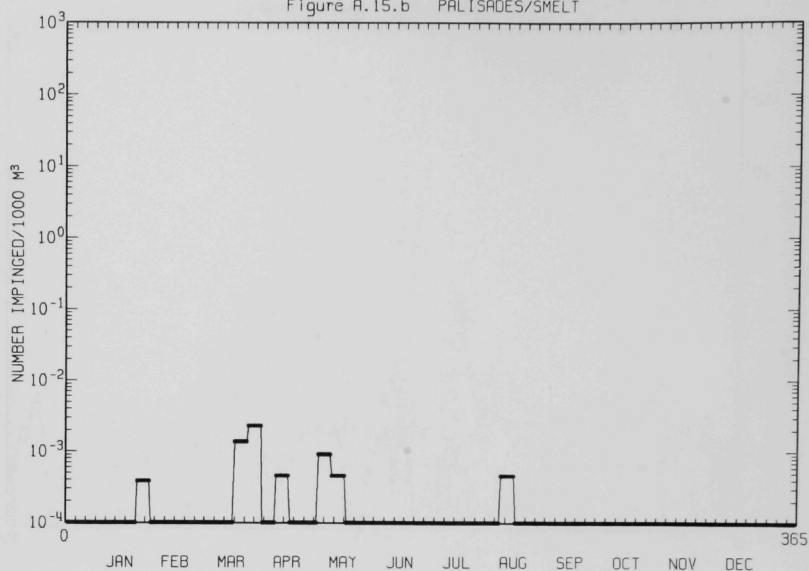


Figure A.16.b BIG ROCK/SMELT

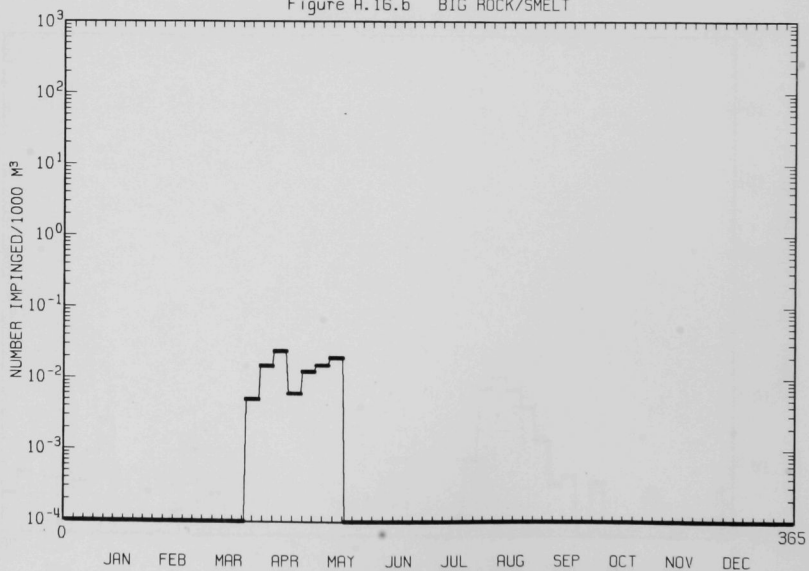


Figure A. 1.c ZION/Y.PERCH

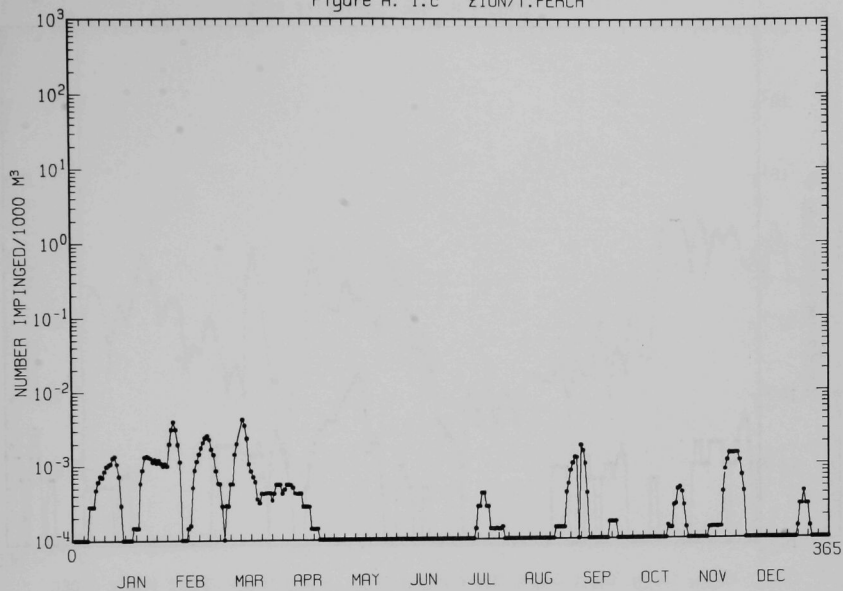
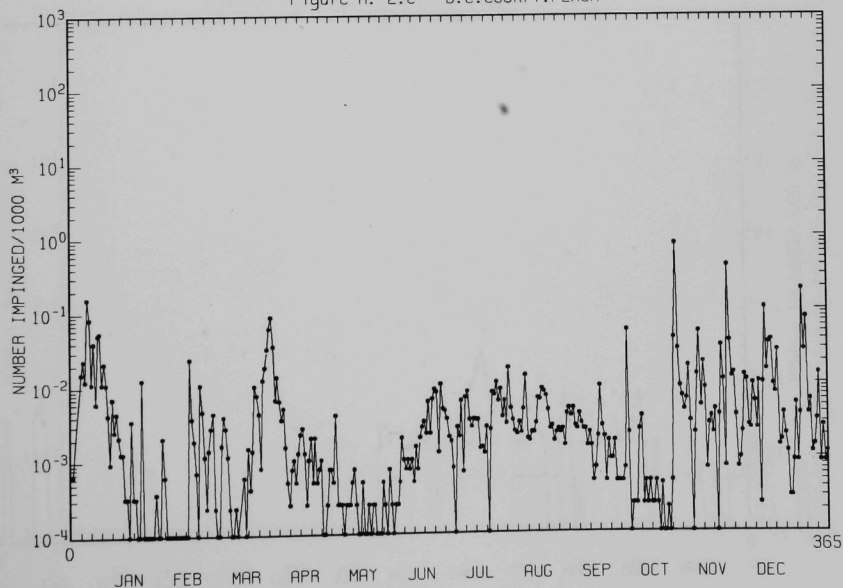


Figure A. 2.c D.C.COOK/Y.PERCH



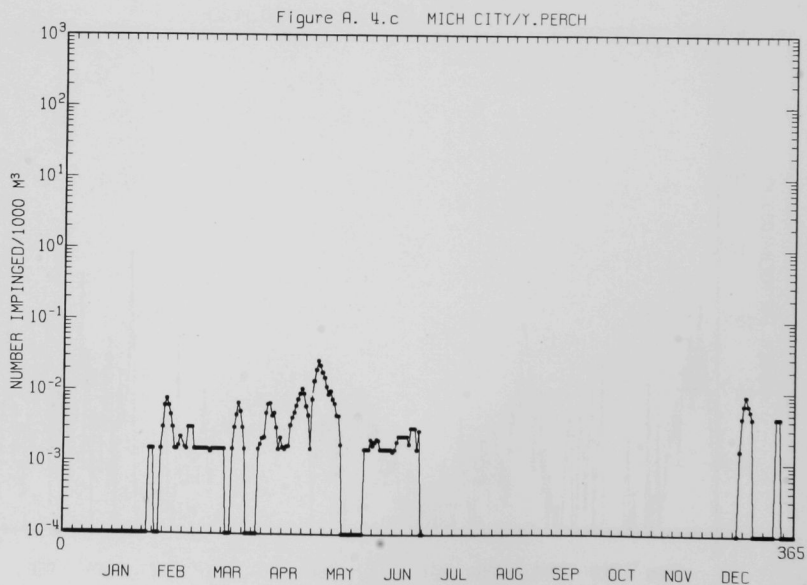
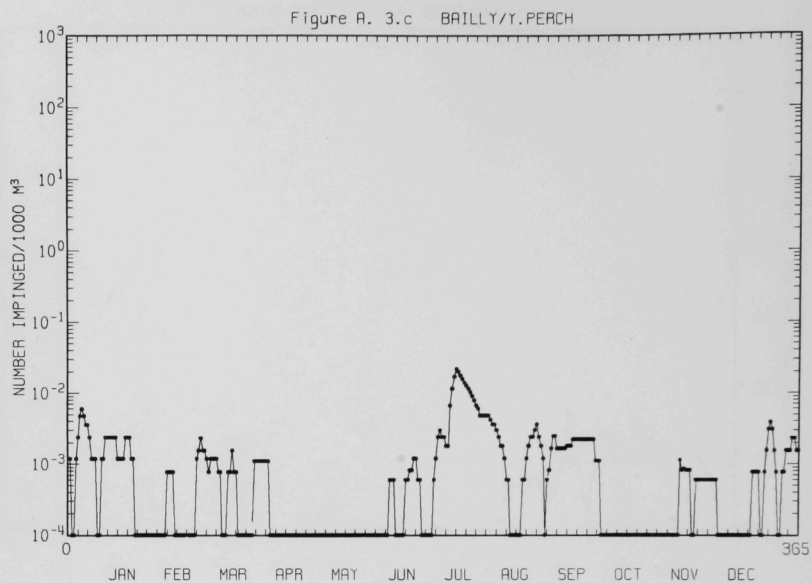


Figure A. 5.c PULLIAM/Y.PERCH

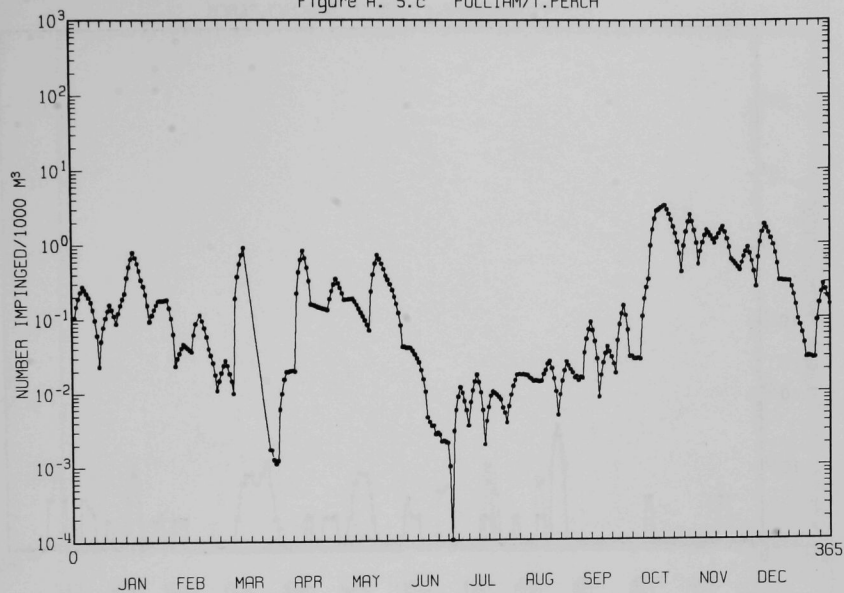


Figure A. 6.c KEWAUNEE/Y.PERCH

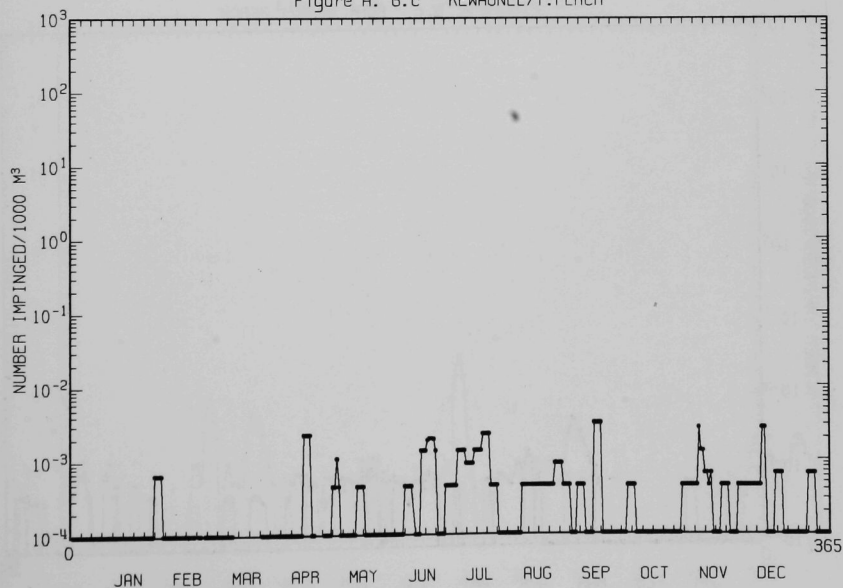


Figure A. 7.c POINT BEACH/Y.PERCH

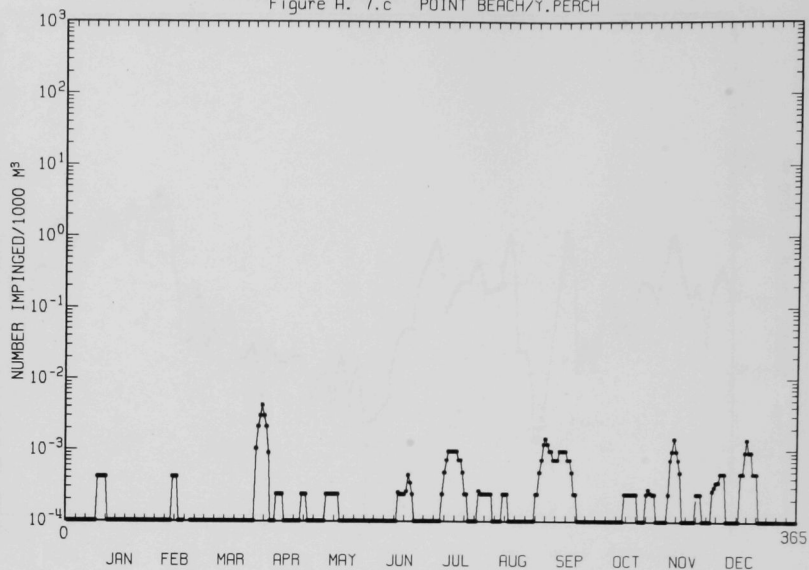


Figure A. 8.c PORT WASH/Y.PERCH

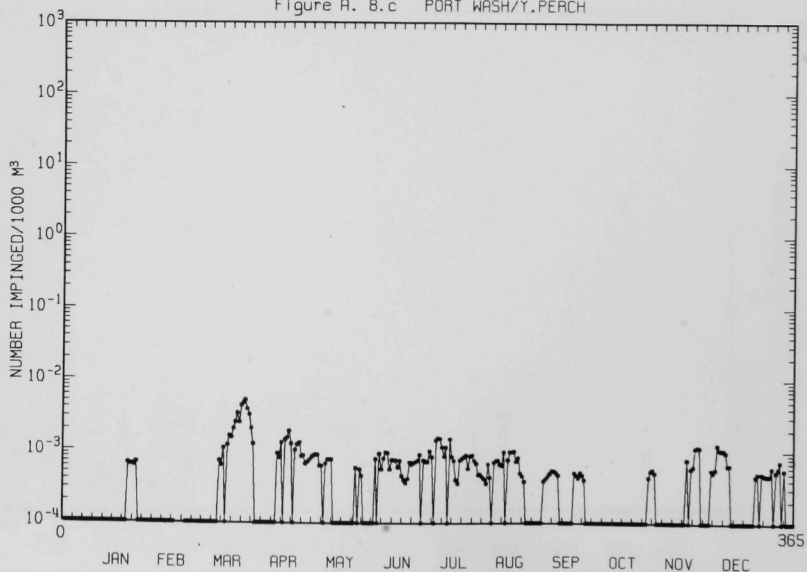


Figure A. 9.c LAKESIDE/Y.PERCH

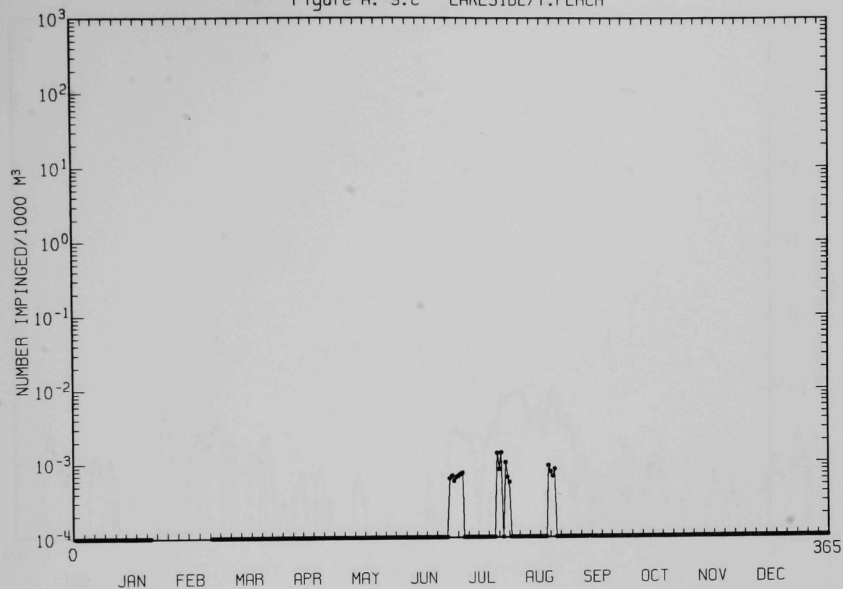


Figure A.10.c OAK CREEK/Y.PERCH

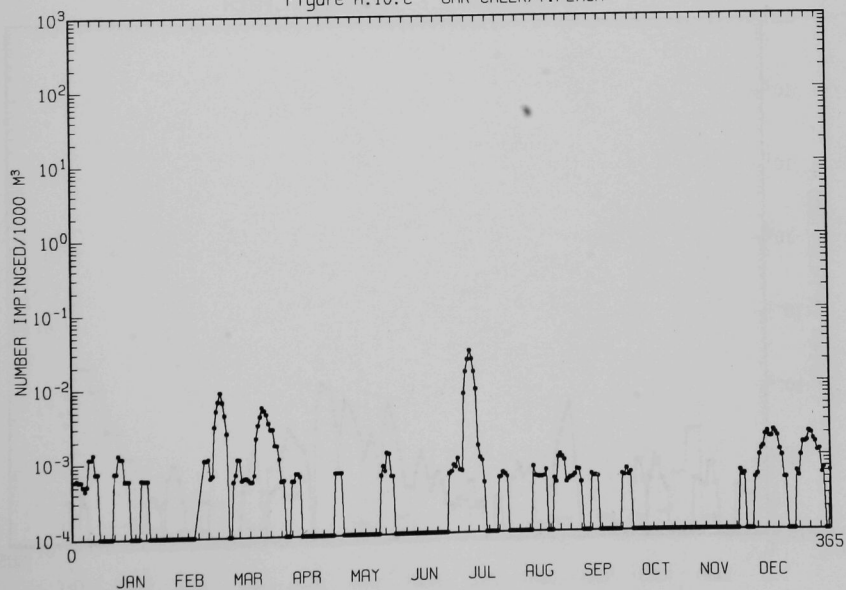


Figure A.11.c WAUKEGAN/Y.PERCH

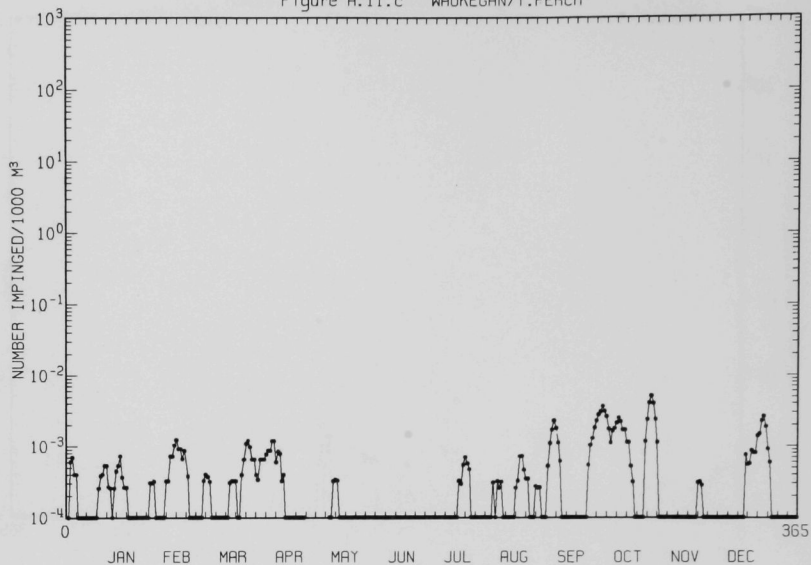


Figure A.12.c STATELINE/Y.PERCH

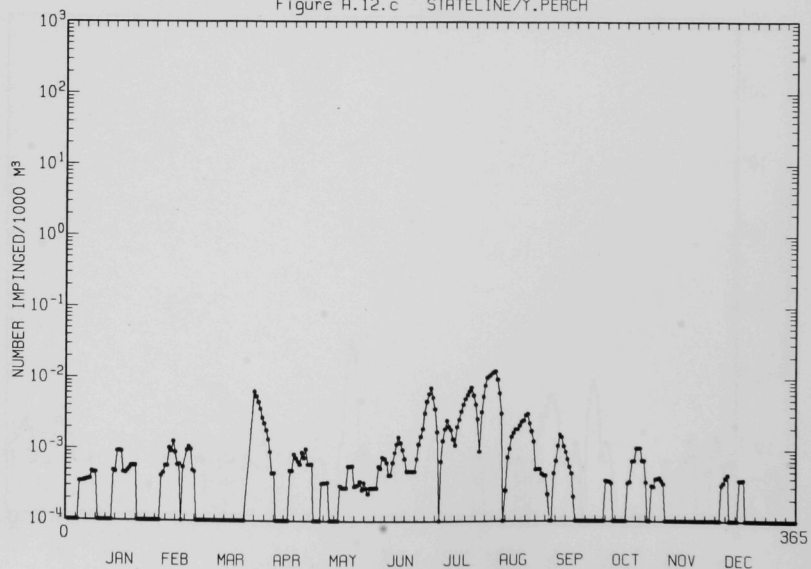


Figure A.13.c MITCHELL/Y.PERCH

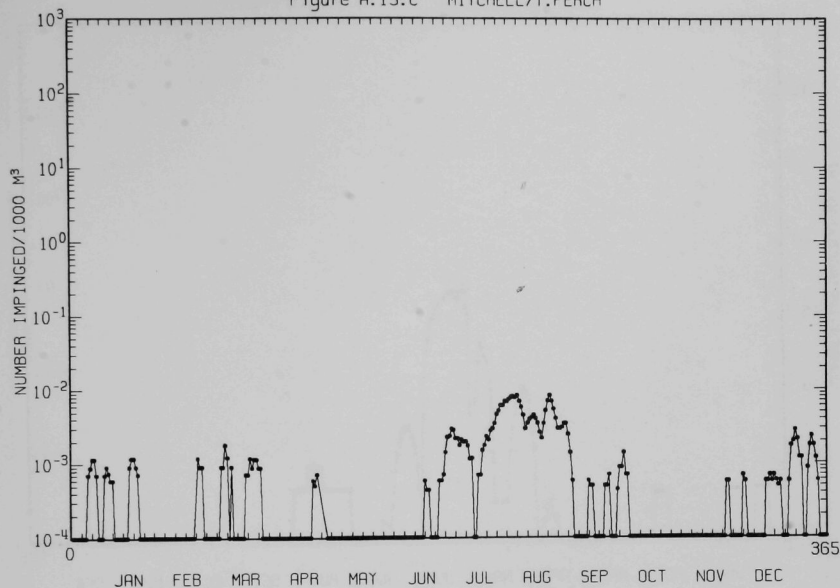


Figure A.14.c CAMPBELL/Y.PERCH

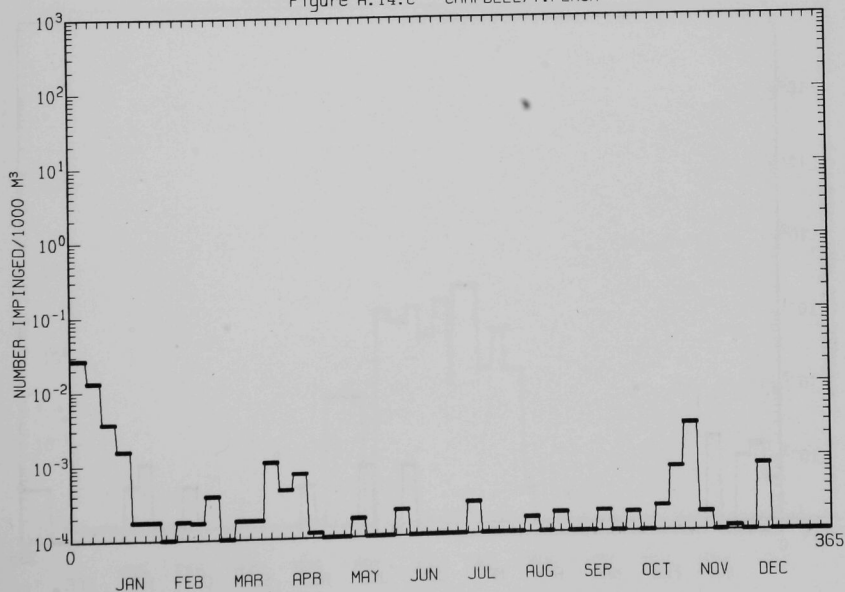


Figure A.15.c PALISADES/Y.PEACH

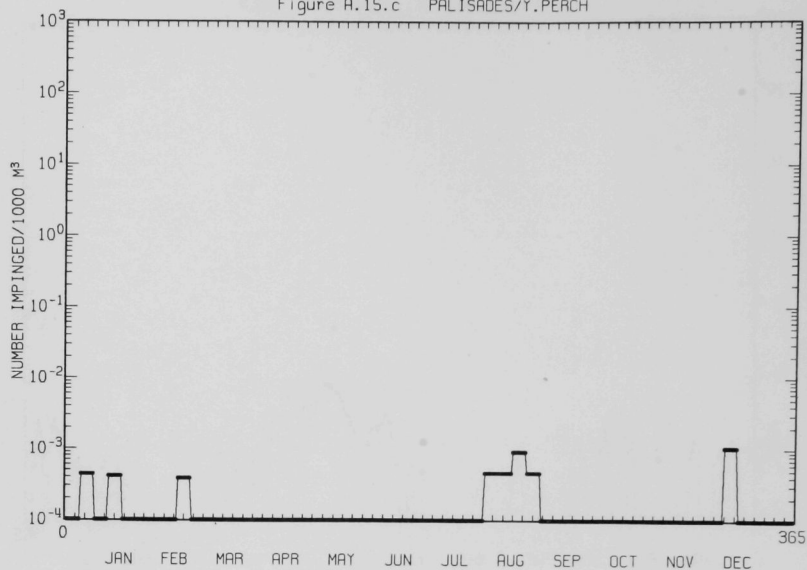


Figure A.16.c BIG ROCK/Y.PEACH

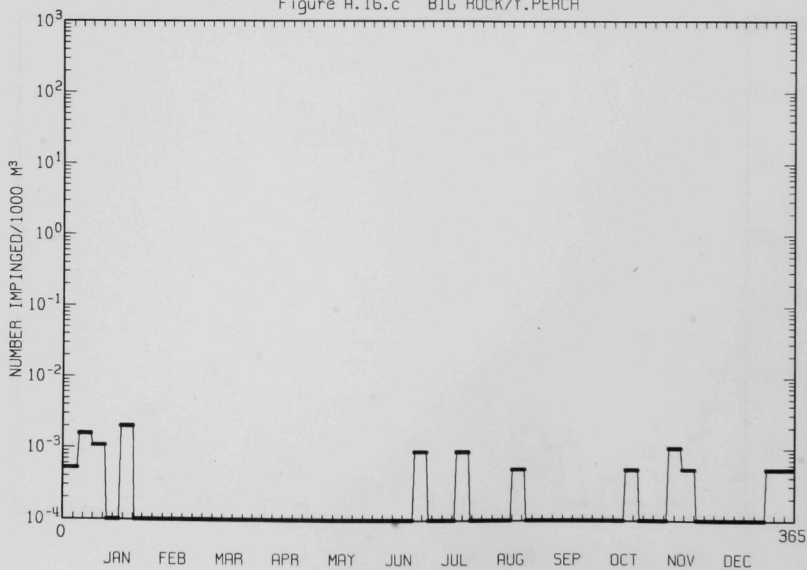


Figure A. 1.d ZION/ALEWIFE EGGS

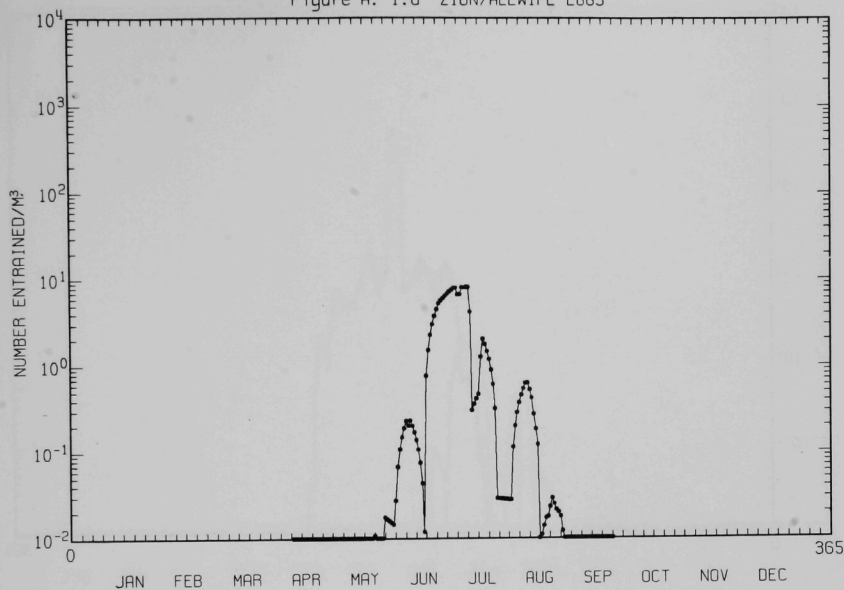


Figure A. 2.d D.C. COOK/ALEWIFE EGGS

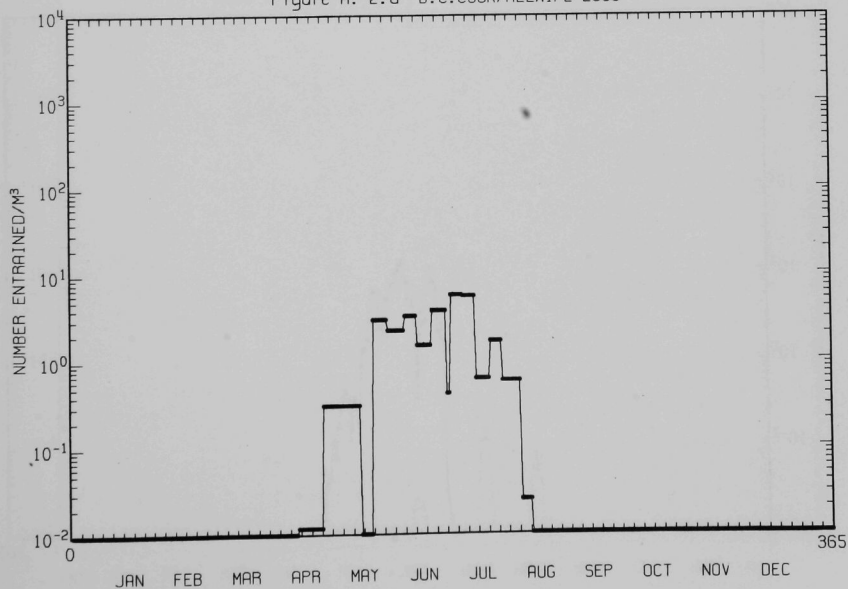


Figure A. 3.d BAILLY/ALEWIFE EGGS

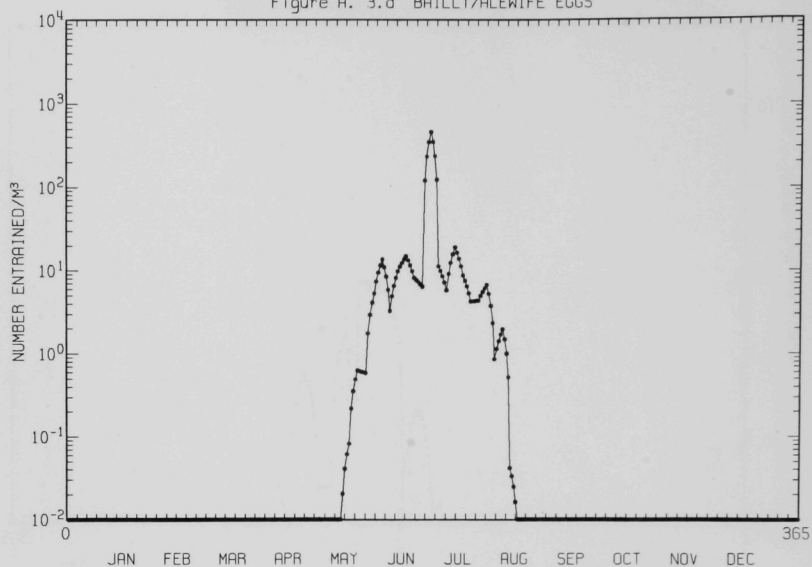


Figure A. 5.d PULLIAM/ALEWIFE EGGS

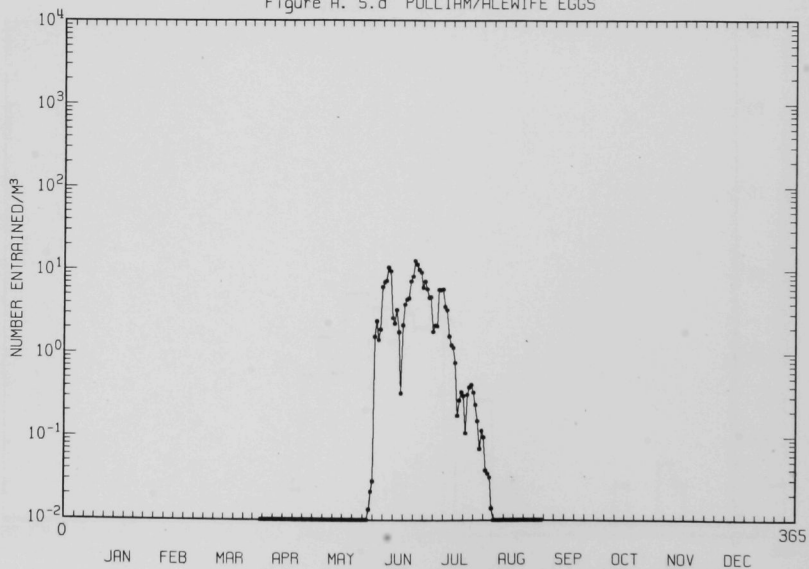


Figure A. 6.d KEWAUNEE/ALEWIFE EGGS

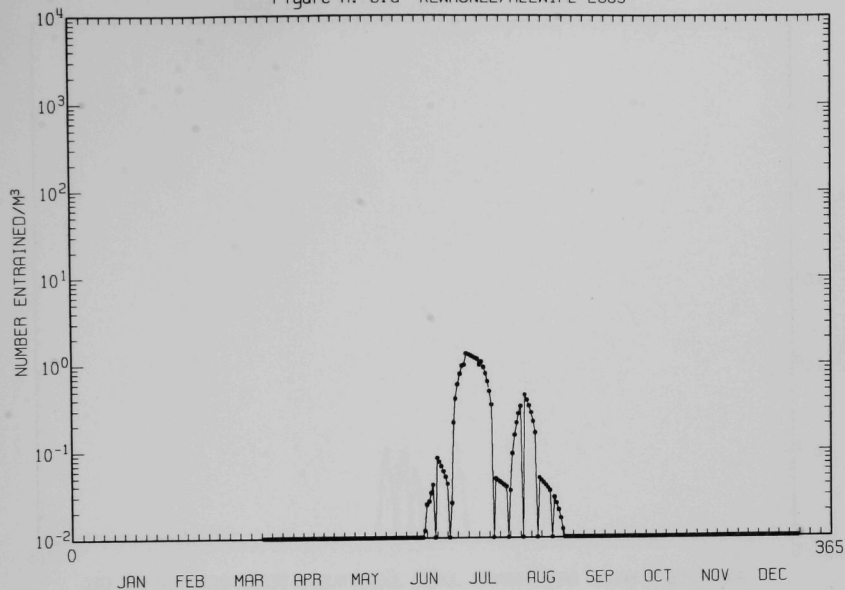


Figure A. 7.d PT BEACH/ALEWIFE EGGS

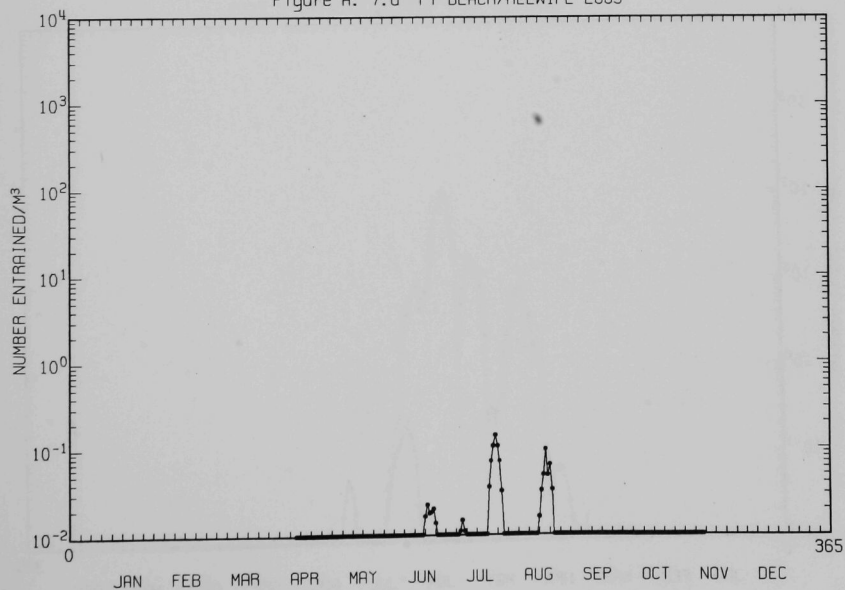


Figure A. 8.d PORT WASH/ALEWIFE EGGS

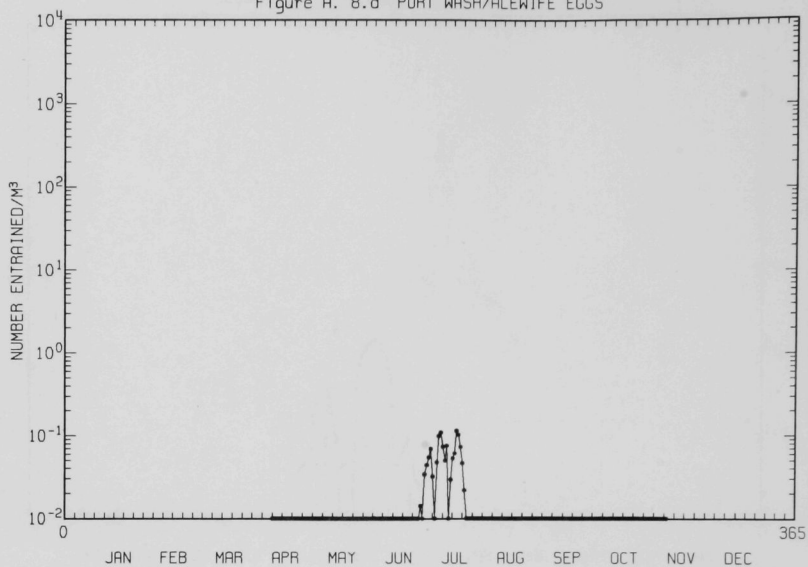


Figure A. 9.d LAKESIDE/ALEWIFE EGGS

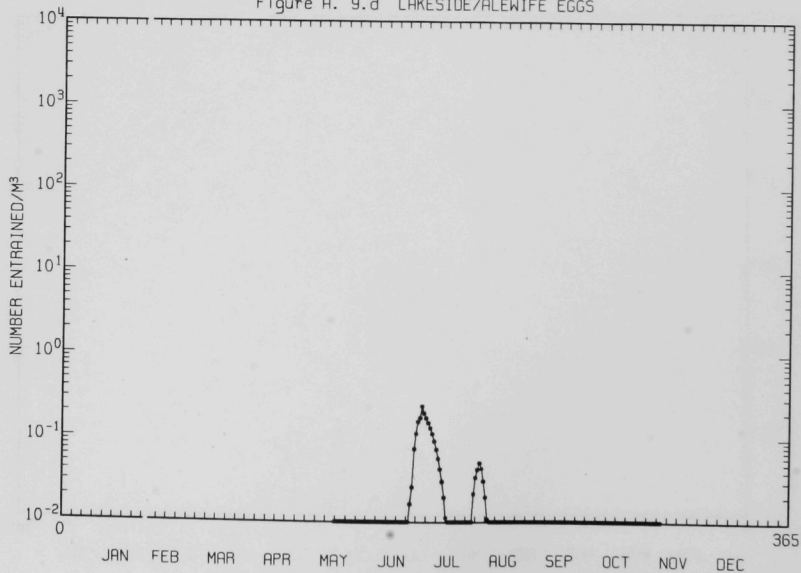


Figure A.10.d OAK CREEK/ALEWIFE EGGS

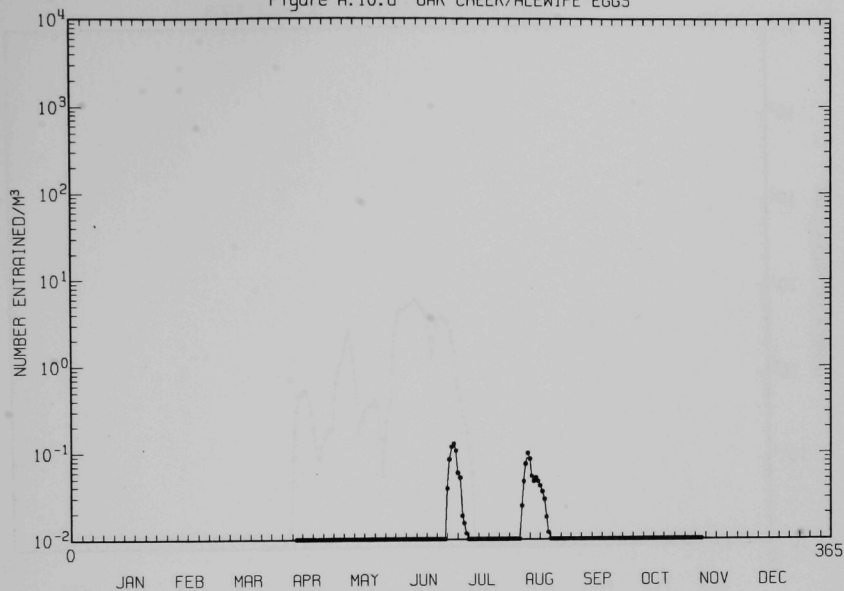


Figure A.11.d WAUKEGAN/ALEWIFE EGGS

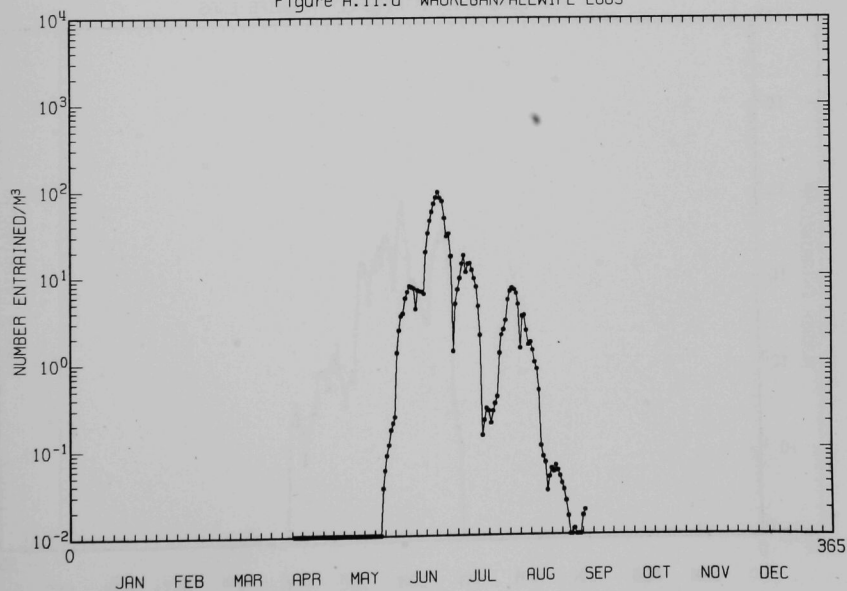


Figure A.12.d STATELINE/ALEWIFE EGGS

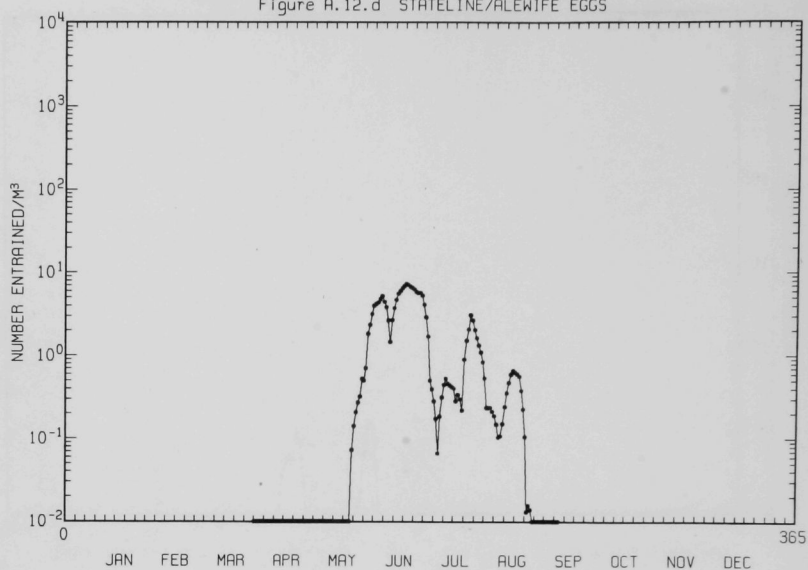


Figure A.13.d MITCHELL/ALEWIFE EGGS

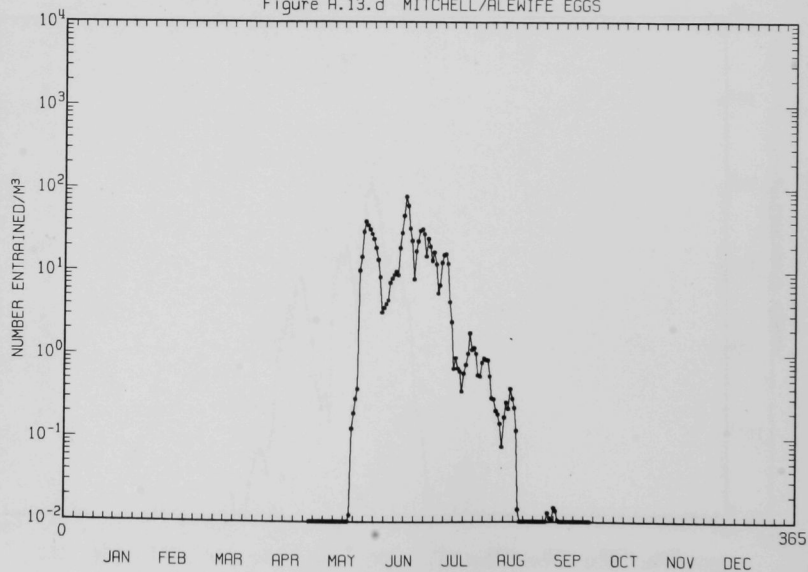


Figure A.14.d CAMPBELL/ALEWIFE EGGS

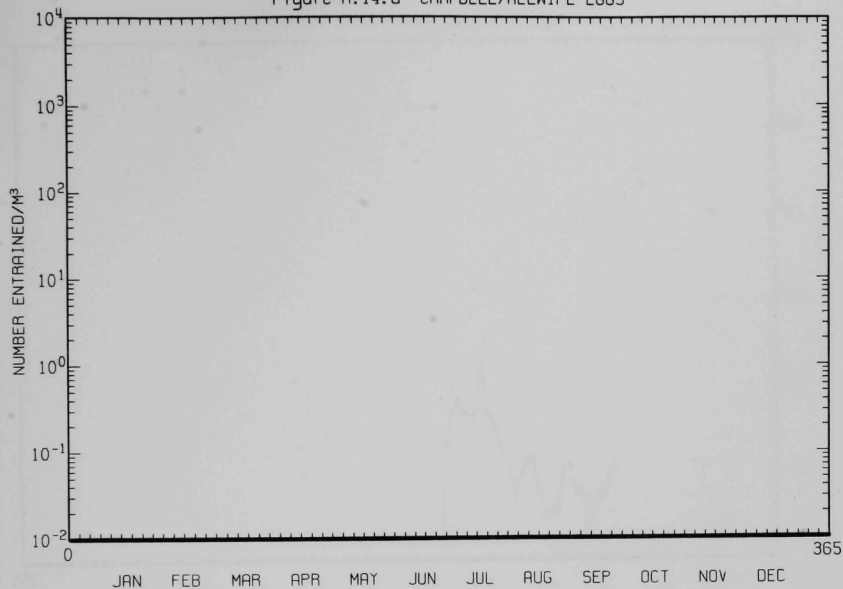


Figure A.15.d PALISADES/ALEWIFE EGGS

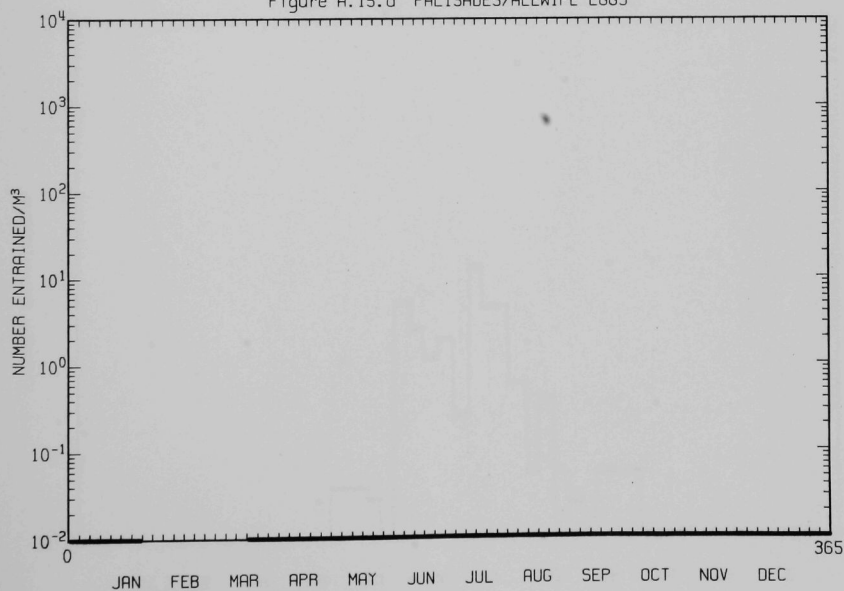


Figure A.16.d BIG ROCK/ALEWIFE EGGS

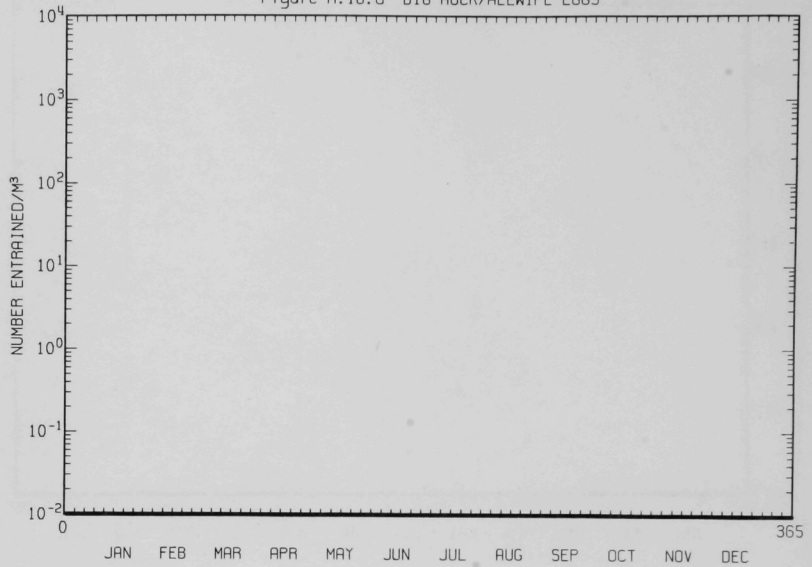


Figure A. 1.e ZION/ALEWIFE LARVAE

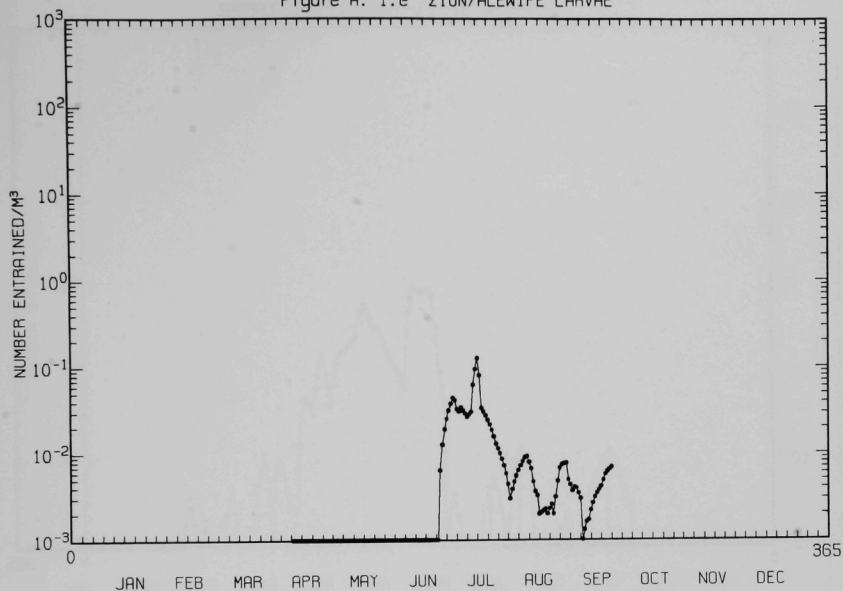


Figure A. 2.e D.C. COOK/ALEWIFE LARVAE

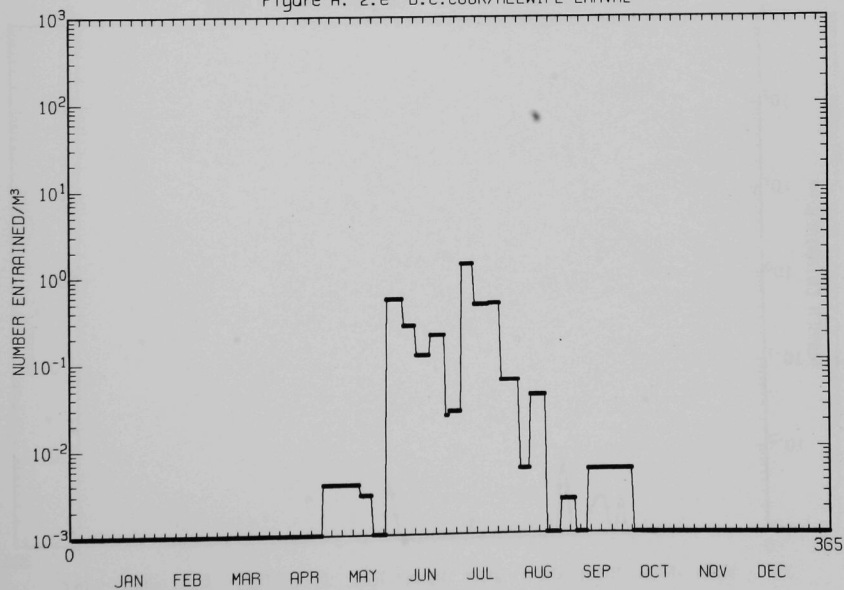


Figure A. 3.e BAILLY/ALEWIFE LARVAE

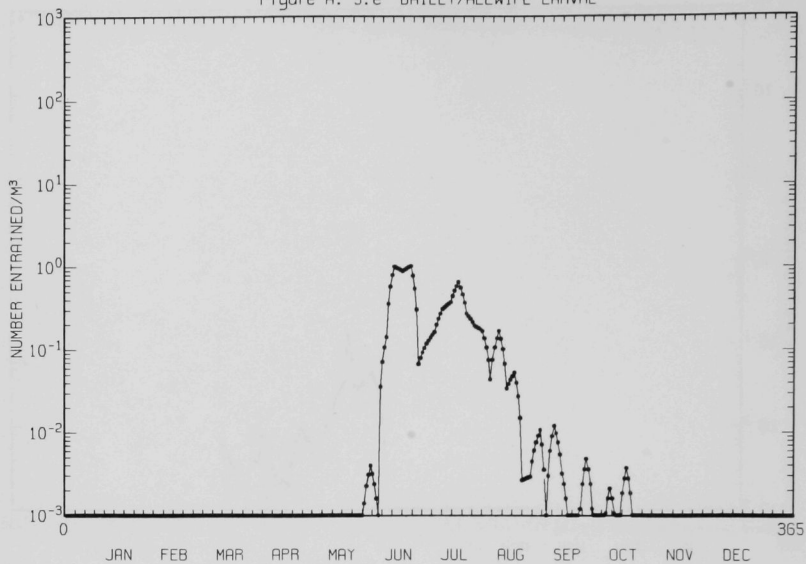


Figure A. 5.e PULLIAM/ALEWIFE LARVAE

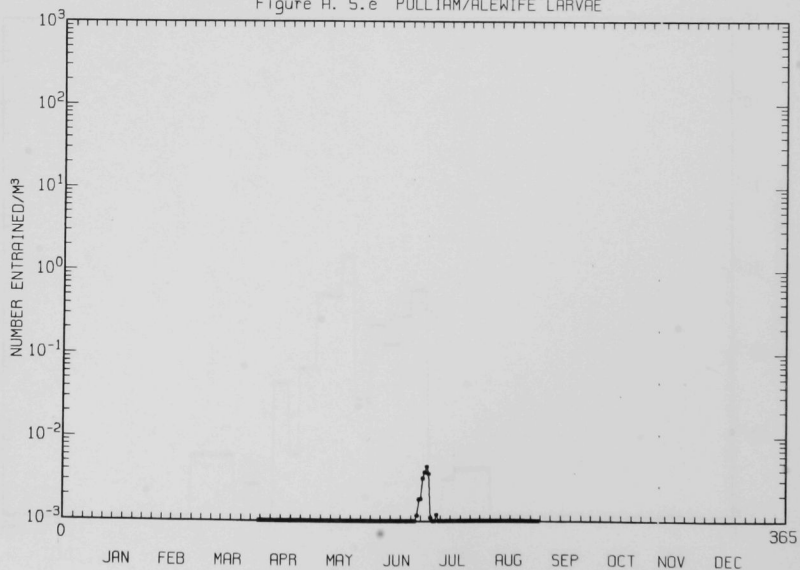


Figure A. 6.e KEWAUNEE/ALEWIFE LARVAE

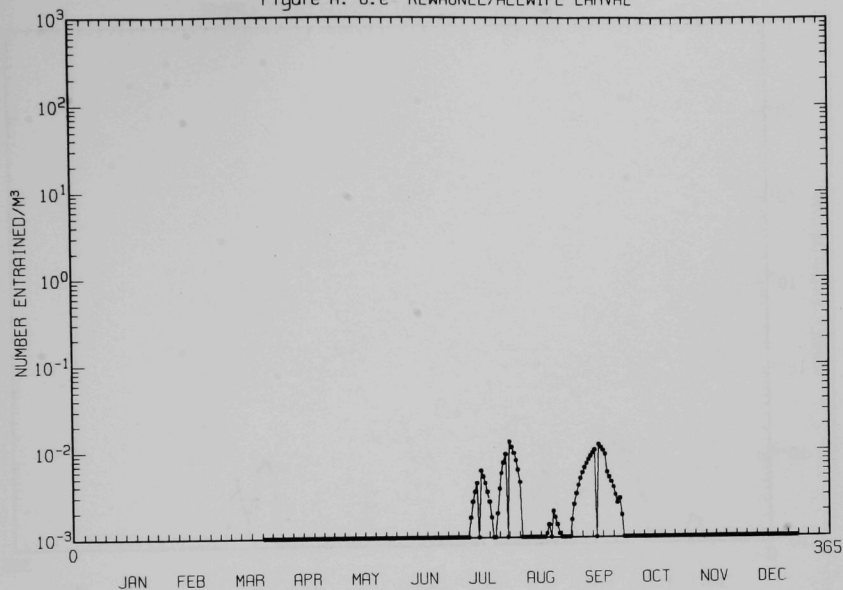


Figure A. 7.e PT BEACH/ALEWIFE LARVAE

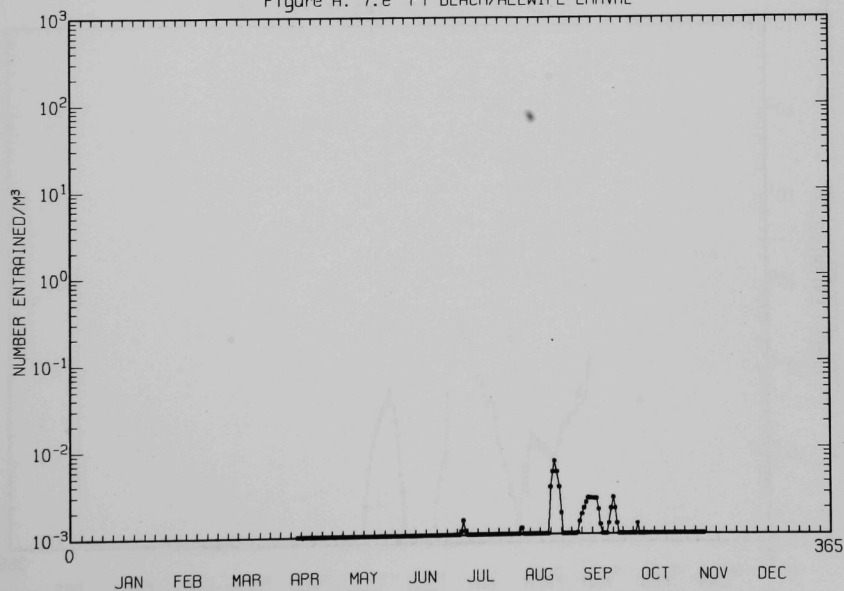
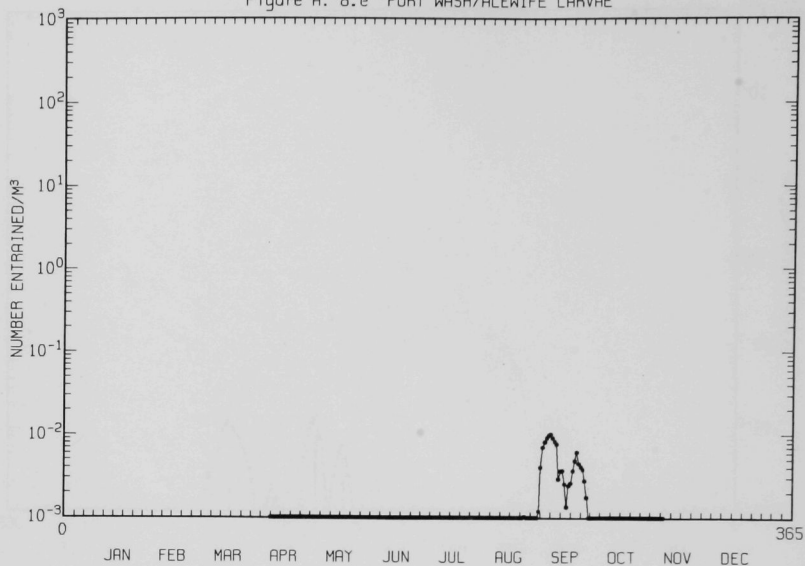


Figure A. 8.e PORT WASH/ALEWIFE LARVAE



• Figure A. 9.e LAKESIDE/ALEWIFE LARVAE

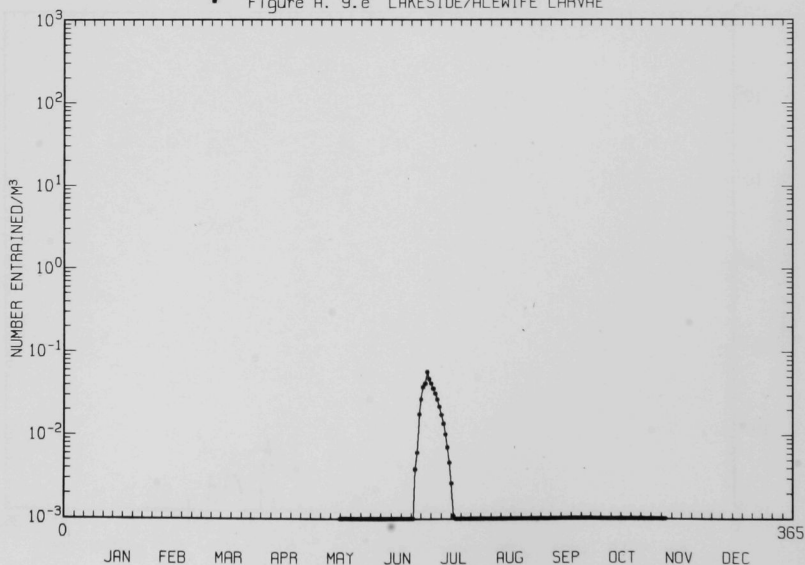


Figure A.10.e OAK CREEK/ALEWIFE LARVAE

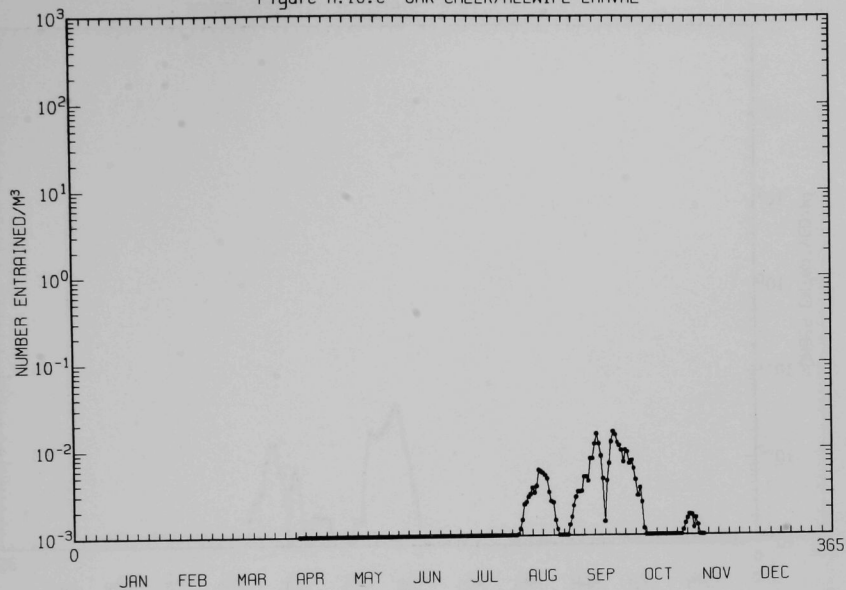


Figure A.11.e WAUKEGAN/ALEWIFE LARVAE

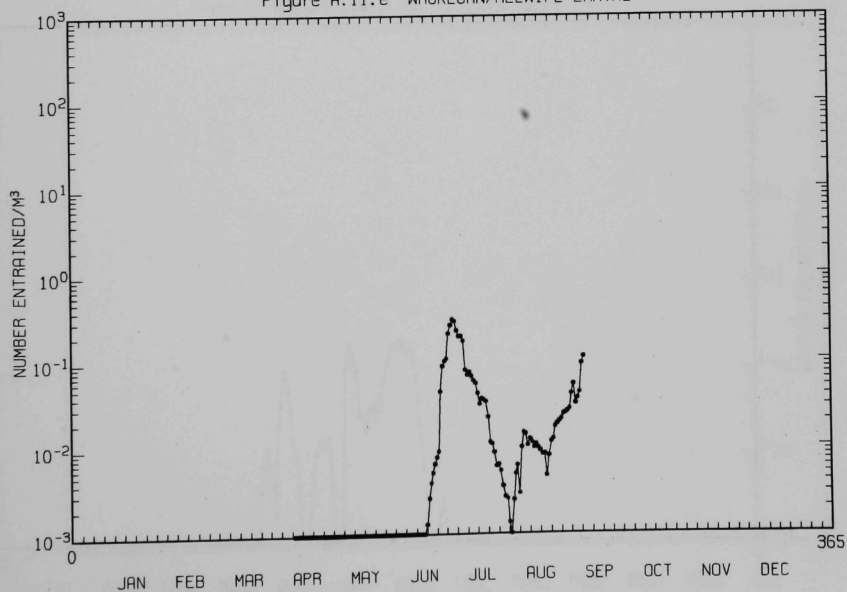


Figure A.12.e STATELINE/ALEWIFE LARVAE

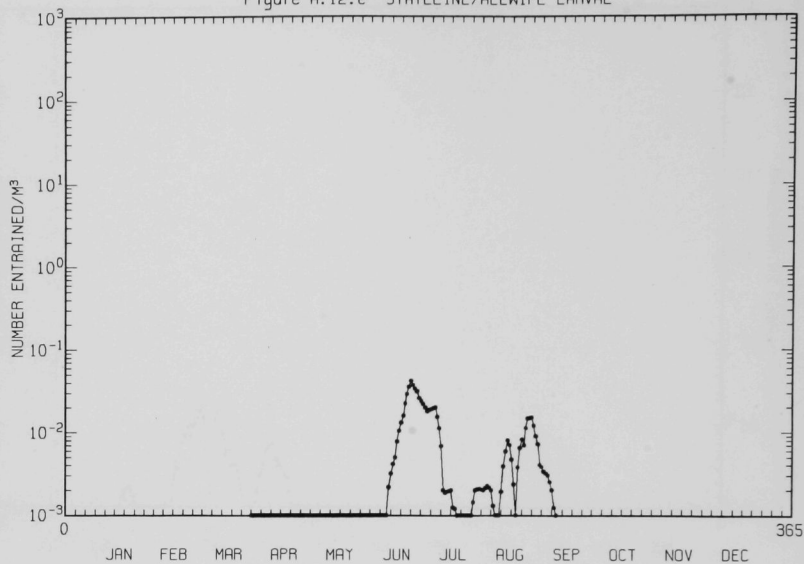


Figure A.13.e MITCHELL/ALEWIFE LARVAE

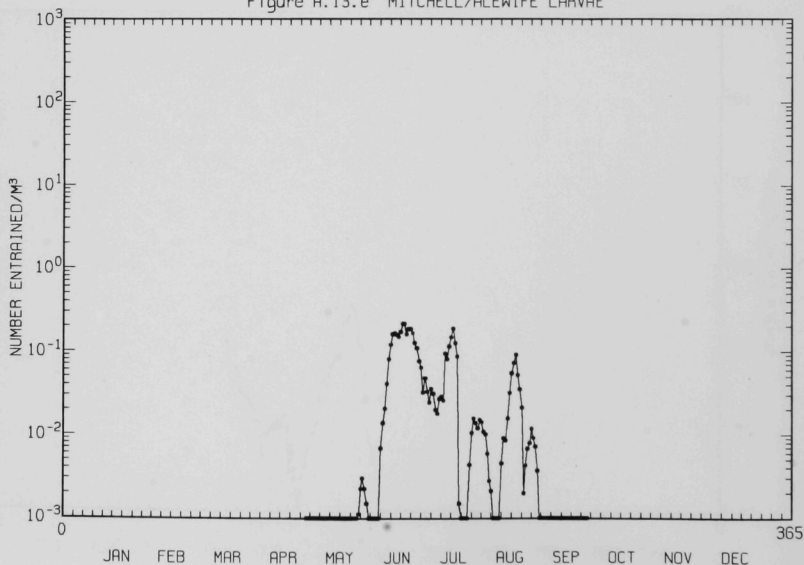


Figure A.14.e CAMPBELL/ALEWIFE LARVAE

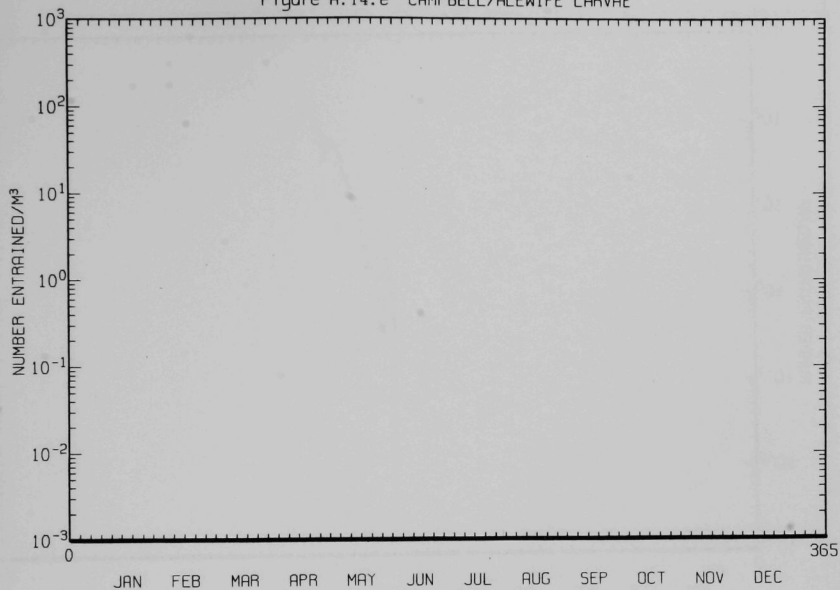


Figure A.15.e PALISADES/ALEWIFE LARVAE

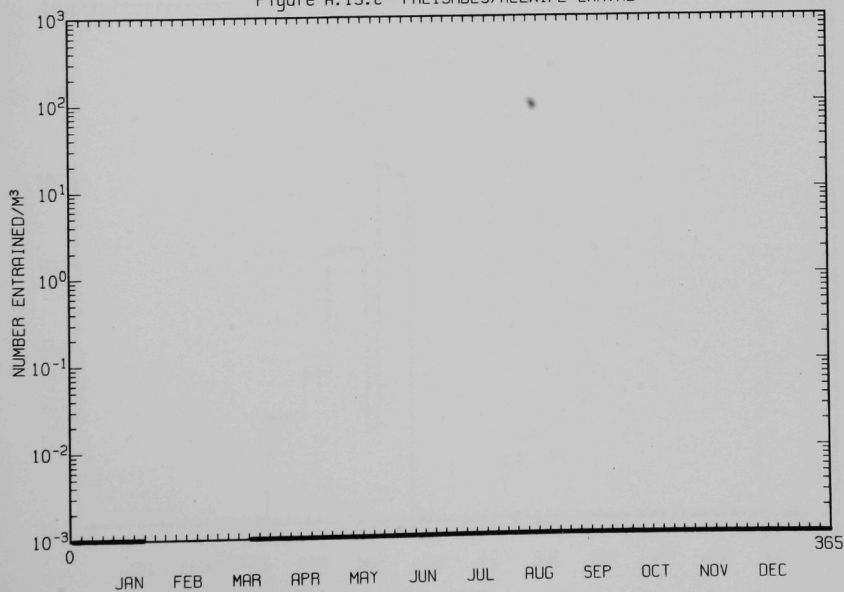


Figure A.16.e BIG ROCK/ALEWIFE LARVAE

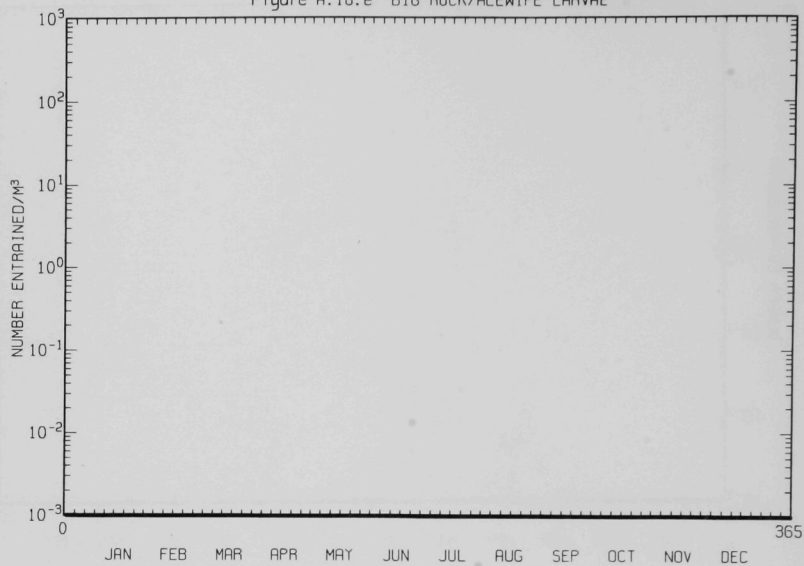


Figure A. 1.f ZION/SMELT EGGS

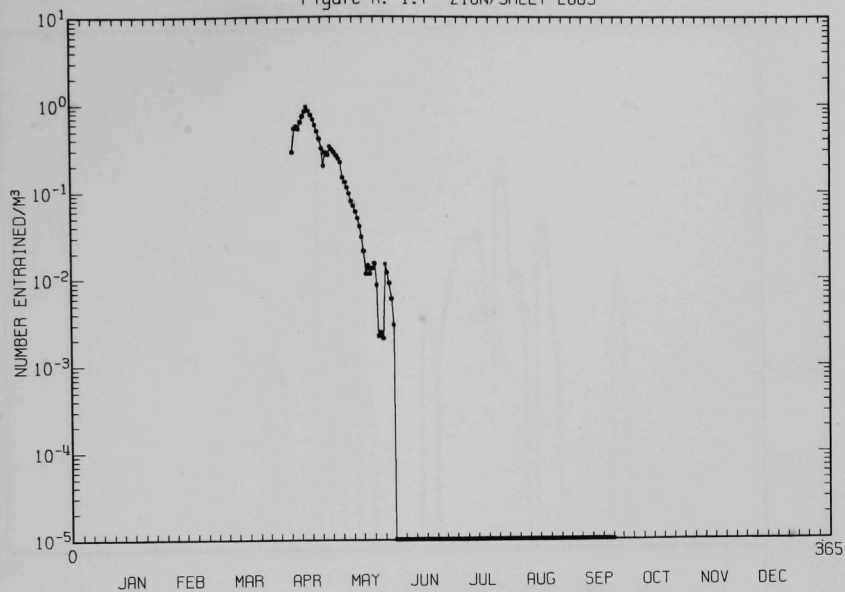


Figure A. 2.f D.C. COOK/SMELT EGGS

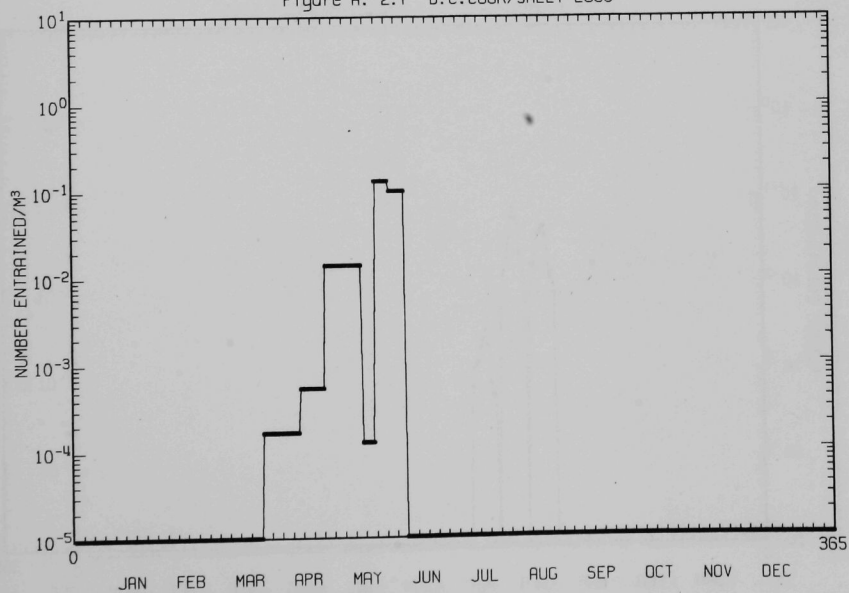


Figure A. 3.f BAILLY/SMELT EGGS

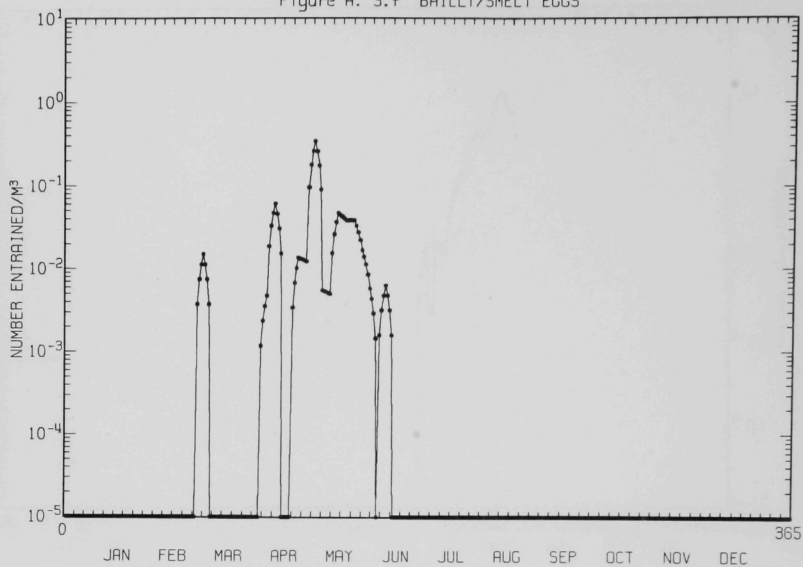


Figure A. 5.f PULLIAM/SMELT EGGS

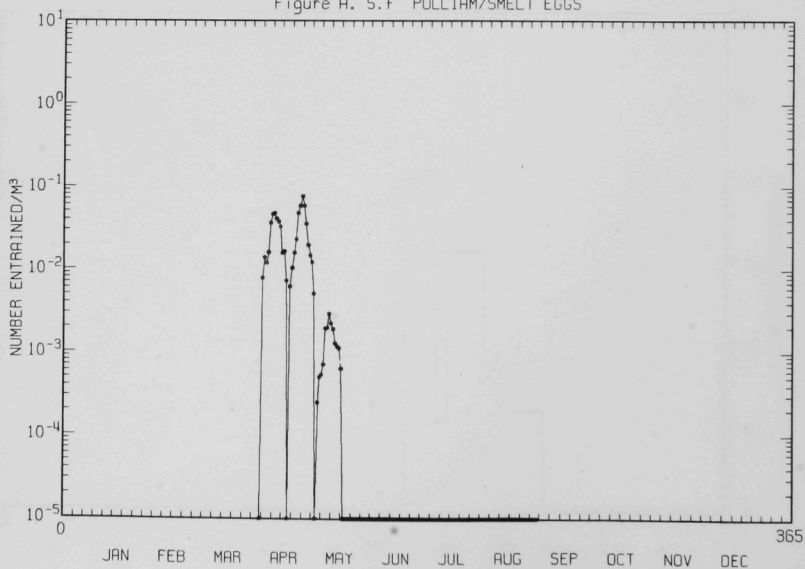


Figure A. 6.f KEWAUNEE/SMELT EGGS

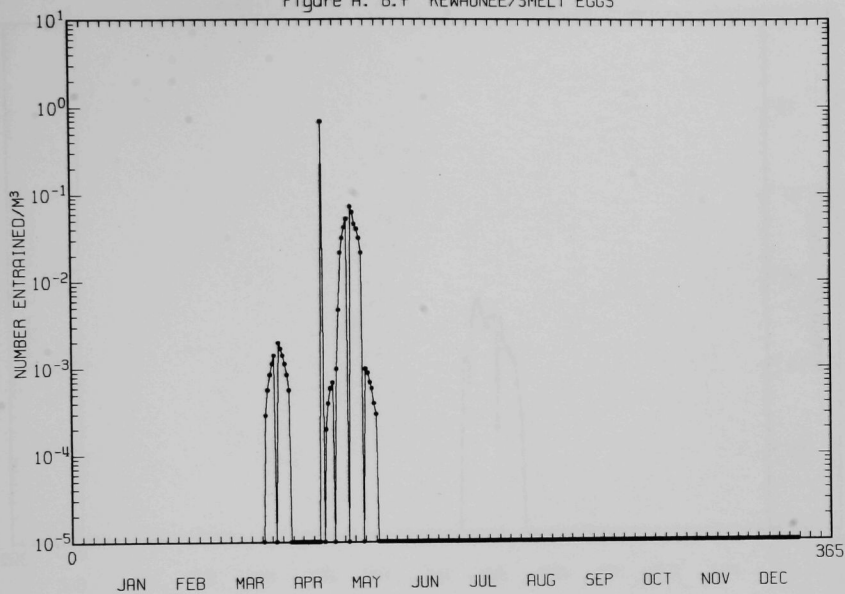


Figure A. 7.f PT BEACH/SMELT EGGS

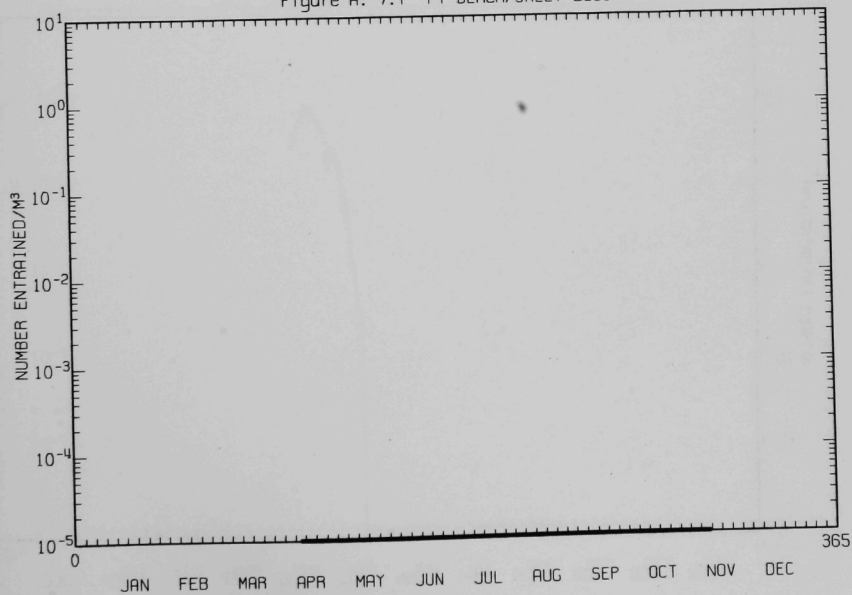


Figure A. 8.f PORT WASH/SMELT EGGS

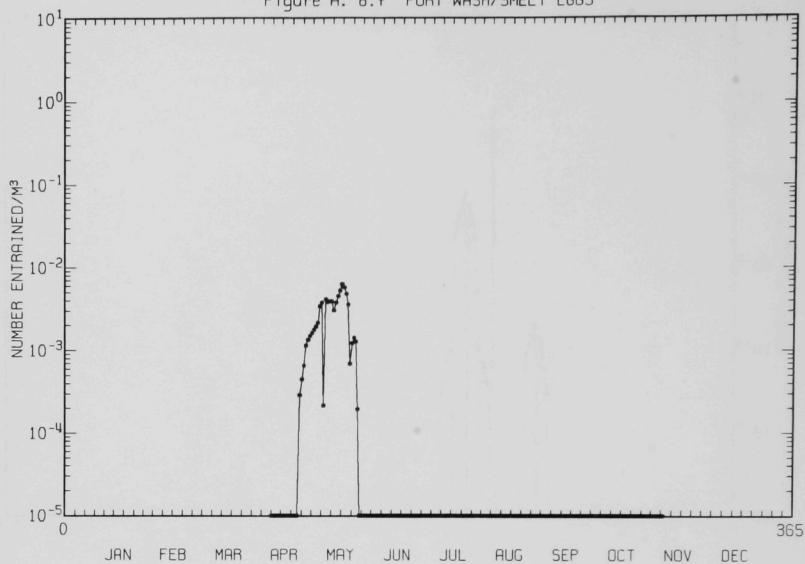


Figure A. 9.f LAKESIDE/SMELT EGGS

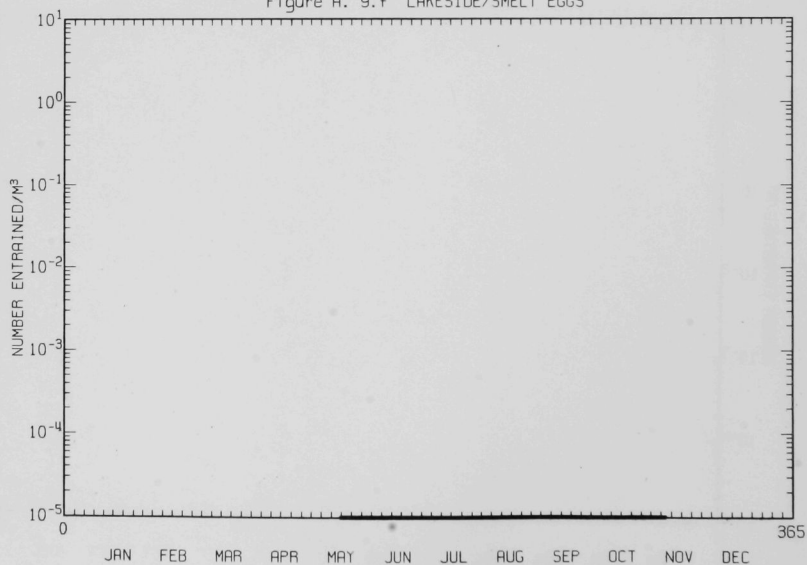


Figure A.10.f OAK CREEK/SMELT EGGS

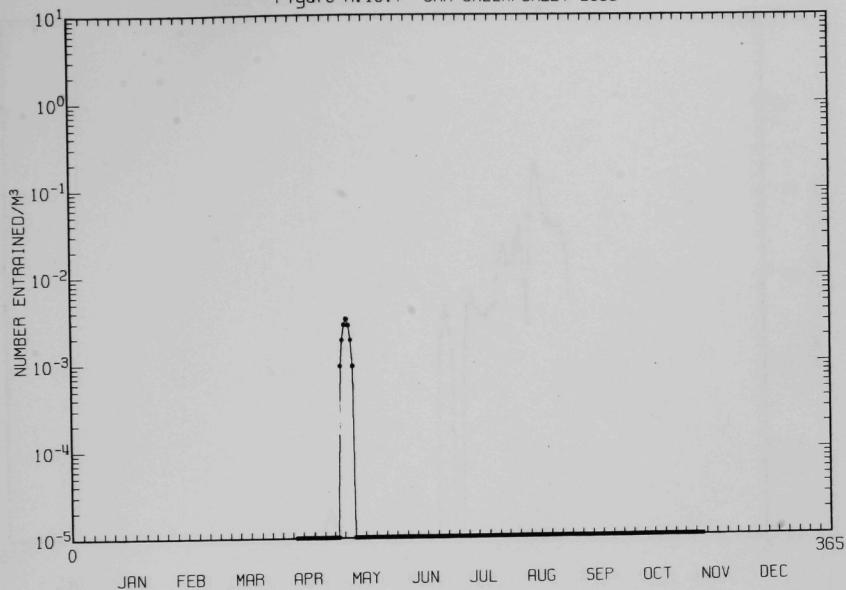


Figure A.11.F WAUKEGAN/SMELT EGGS

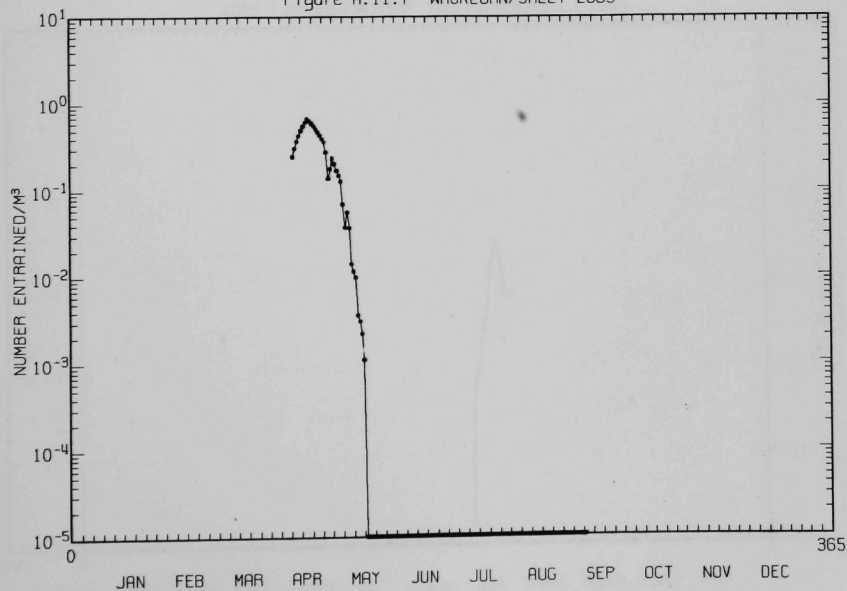


Figure A.12.1 is a line graph showing the number of entrained particles per cubic meter (NUMBER ENTRAINED/M³) versus time (JAN to DEC). The y-axis is logarithmic, ranging from 10^{-5} to 10^1 . The x-axis shows months from JAN to DEC. The data shows a sharp peak in April, reaching approximately 0.2 NUMBER ENTRAINED/M³, followed by a decline and a smaller peak in May. The number of entrained particles is near zero for the rest of the year.

Figure H.13.1 is a semi-logarithmic plot showing the number of entrained Mitchell/Smelt eggs per cubic meter ($\text{NUMBER ENTRAINED}/\text{M}^3$) over time. The y-axis is logarithmic, ranging from 10^{-5} to 10^1 . The x-axis shows months from JAN to DEC. A sharp peak occurs in May, reaching approximately $3 \times 10^{-2} \text{ M}^{-3}$.

Month	Number Entrained (M^{-3})
JAN	0
FEB	0
MAR	0
APR	0
MAY	~0.03
JUN	0
JUL	0
AUG	0
SEP	0
OCT	0
NOV	0
DEC	0

Figure A.14.f CAMPBELL/SMELT EGGS

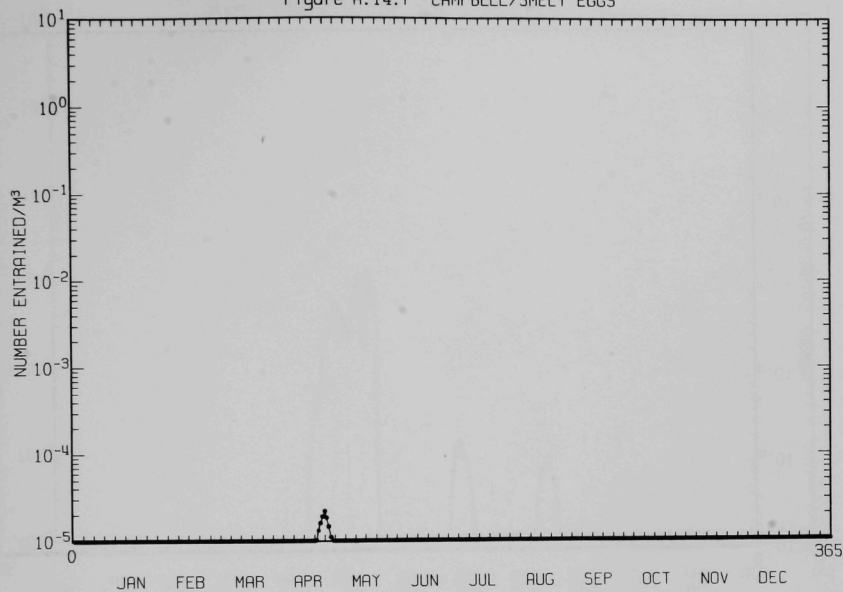


Figure A.15.f PALISADES/SMELT EGGS

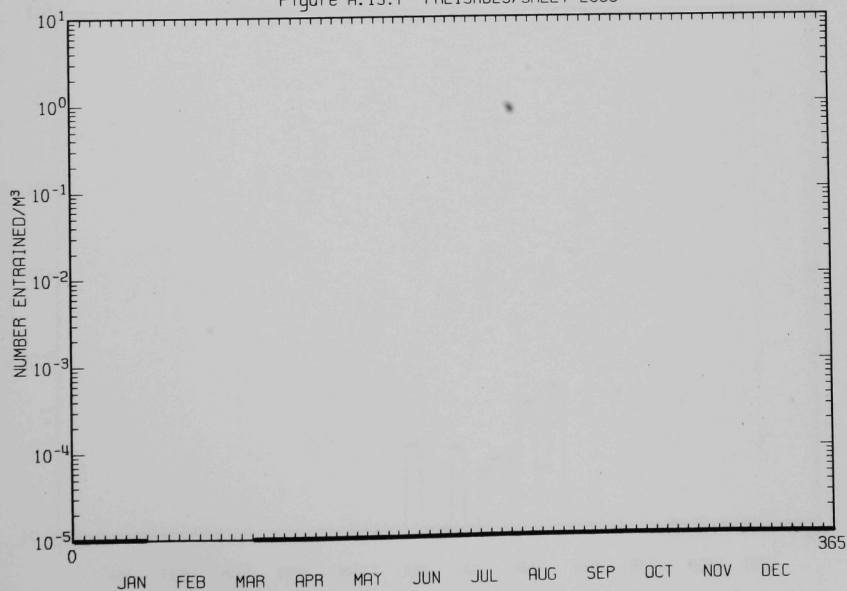


Figure A.16.f BIG ROCK/SMELT EGGS

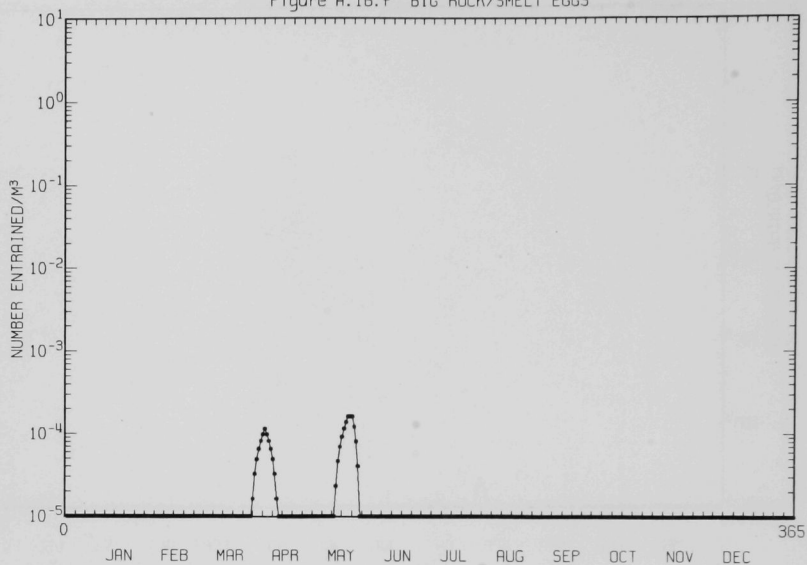


Figure A. 1.g ZION/SMELT LARVAE

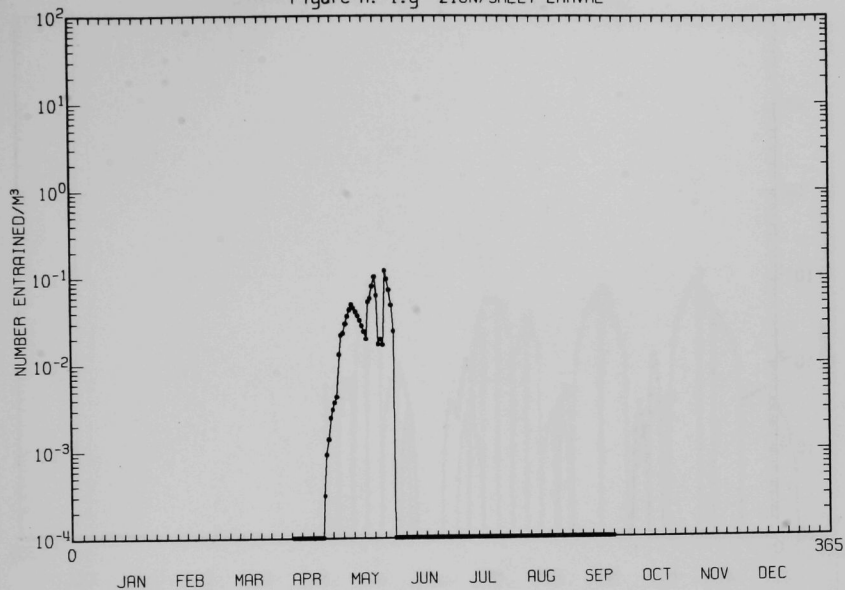


Figure A. 2.g D.C.COOK/SMELT LARVAE

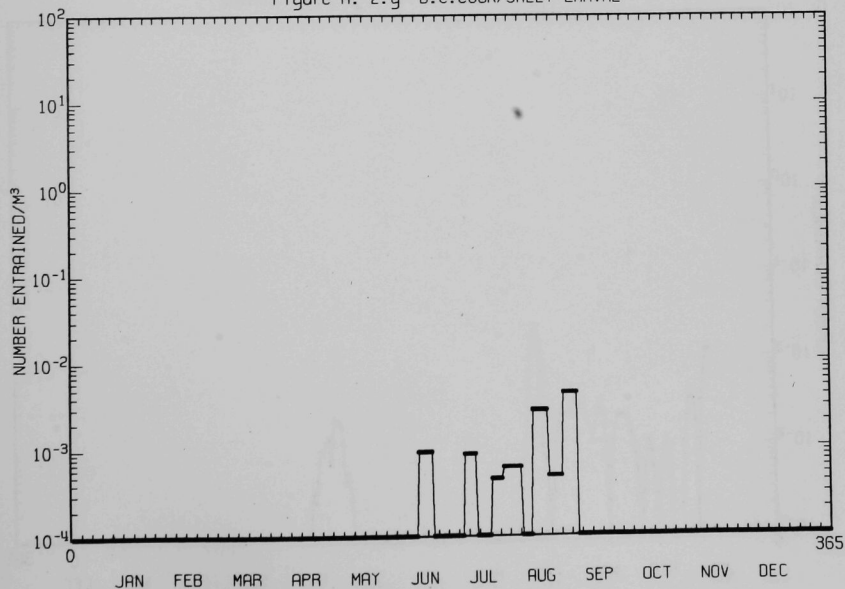


Figure A. 3.g BAILLY/SMELT LARVAE

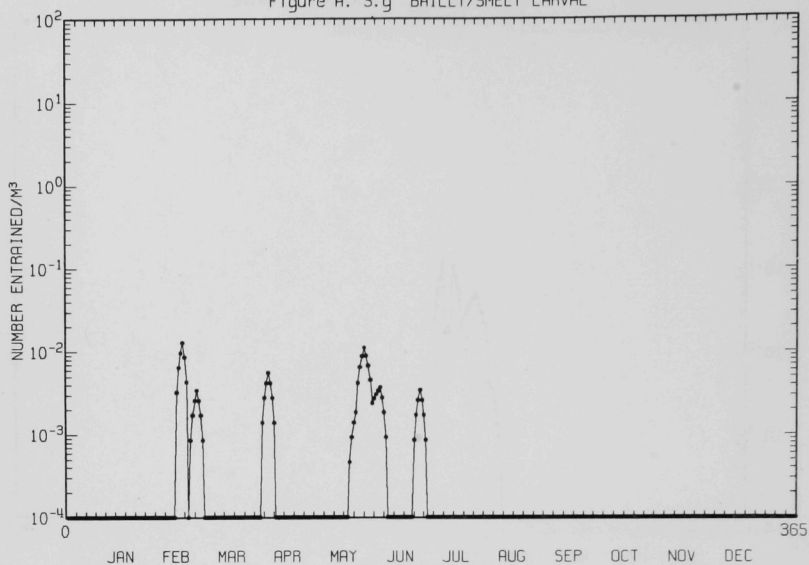


Figure A. 5.g PULLIAM/SMELT LARVAE

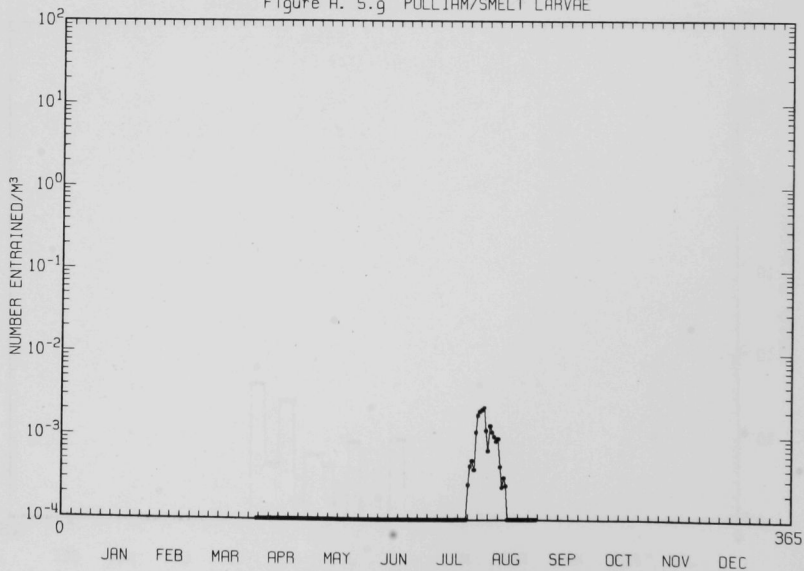


Figure A. 6.g KEWAUNEE/SMELT LARVAE

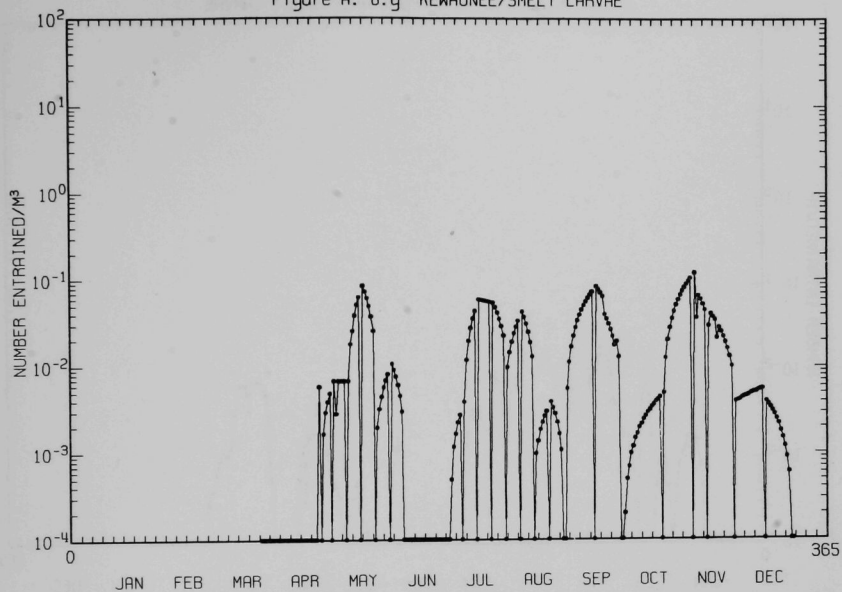


Figure A. 7.g PT BEACH/SMELT LARVAE

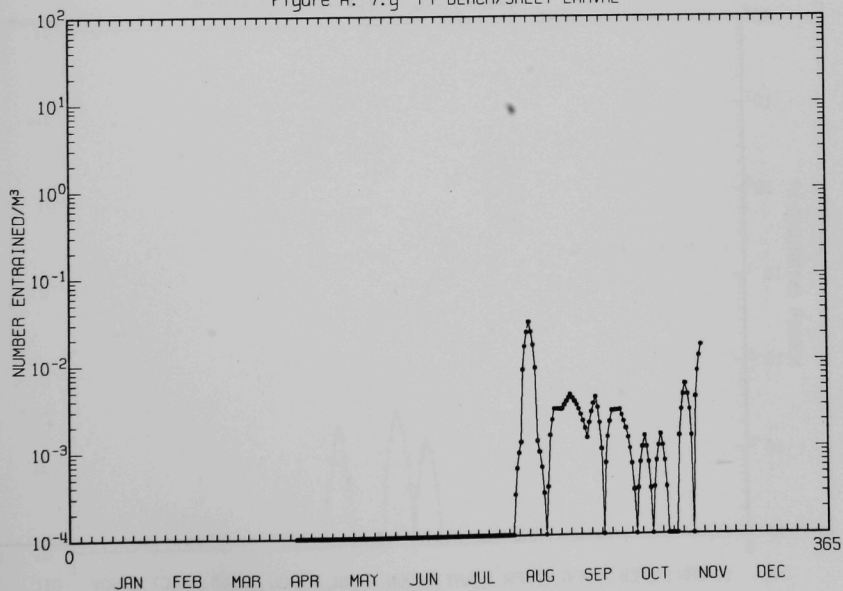


Figure A. 8.g PORT WASH/SMELT LARVAE

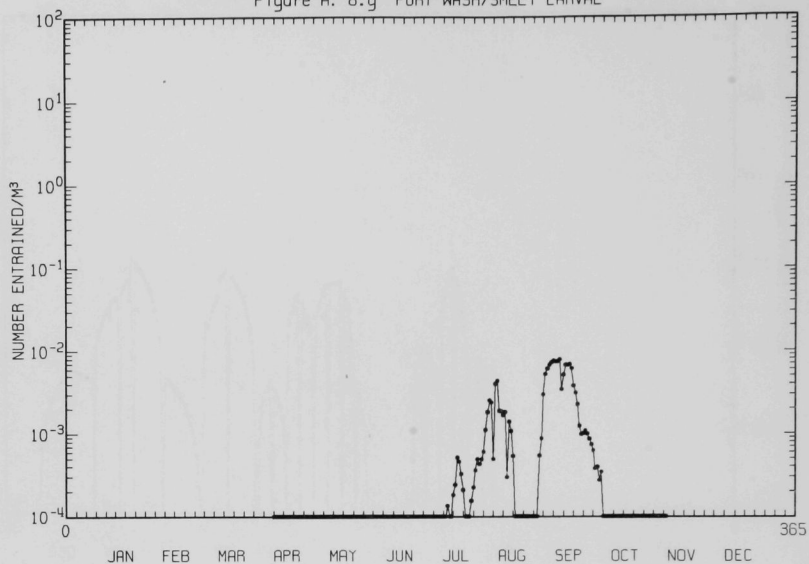


Figure A. 9.g LAKESIDE/SMELT LARVAE

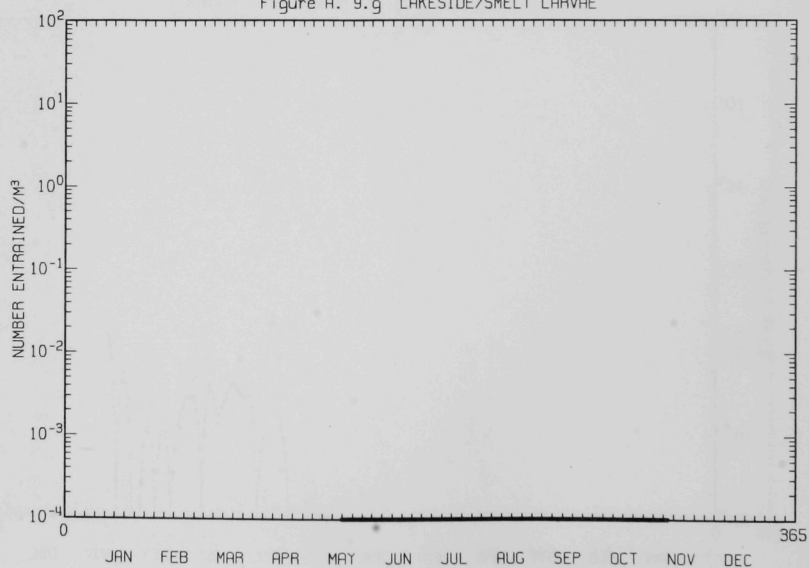


Figure A.10.g OAK CREEK/SMELT LARVAE

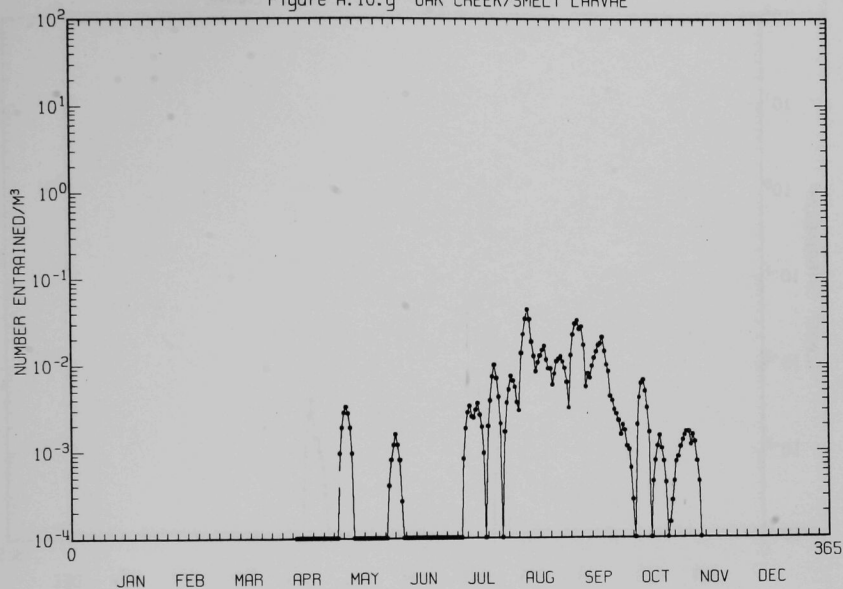


Figure A.11.g WAUKEGAN/SMELT LARVAE

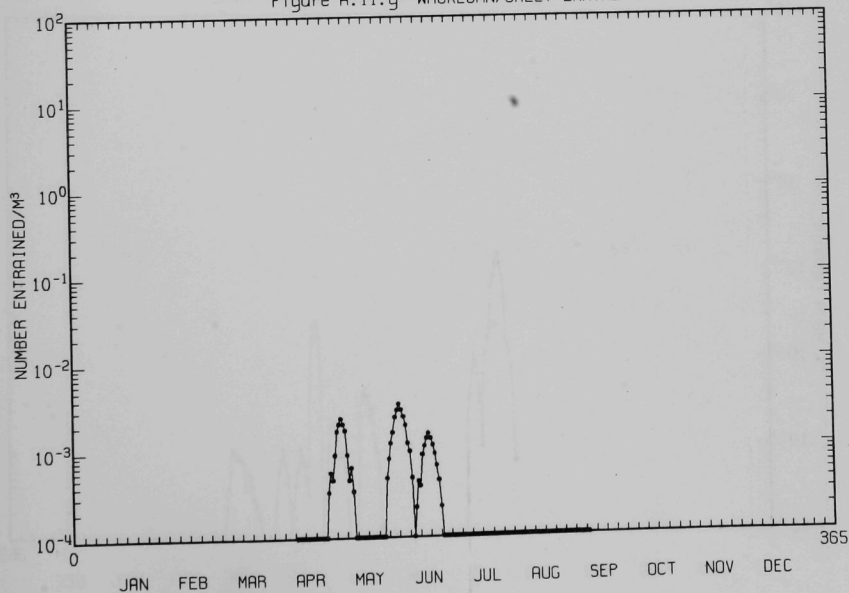


Figure A.12.g STATELINE/SMELT LARVAE

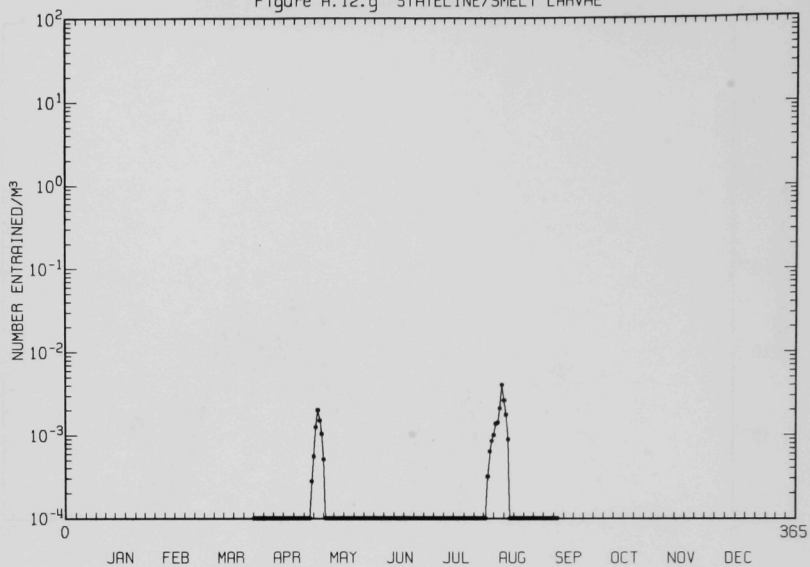


Figure A.13.g MITCHELL/SMELT LARVAE

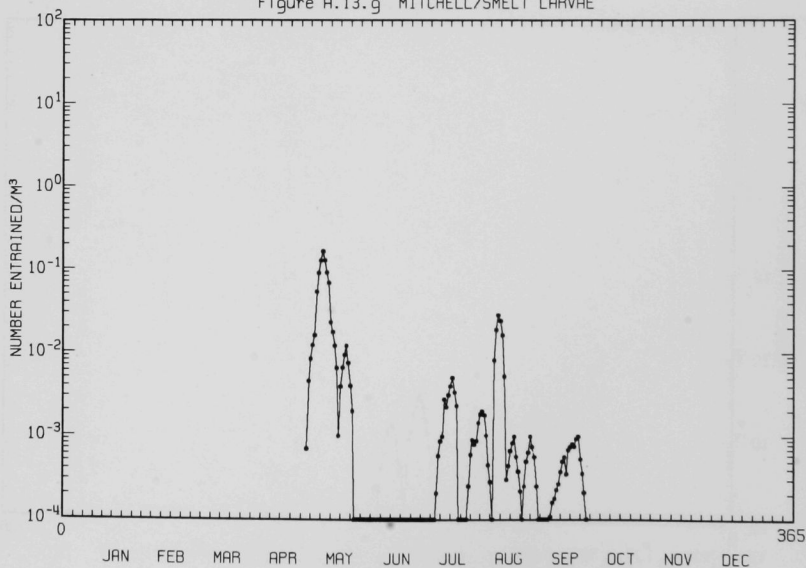


Figure A.14.g CAMPBELL/SMELT LARVAE

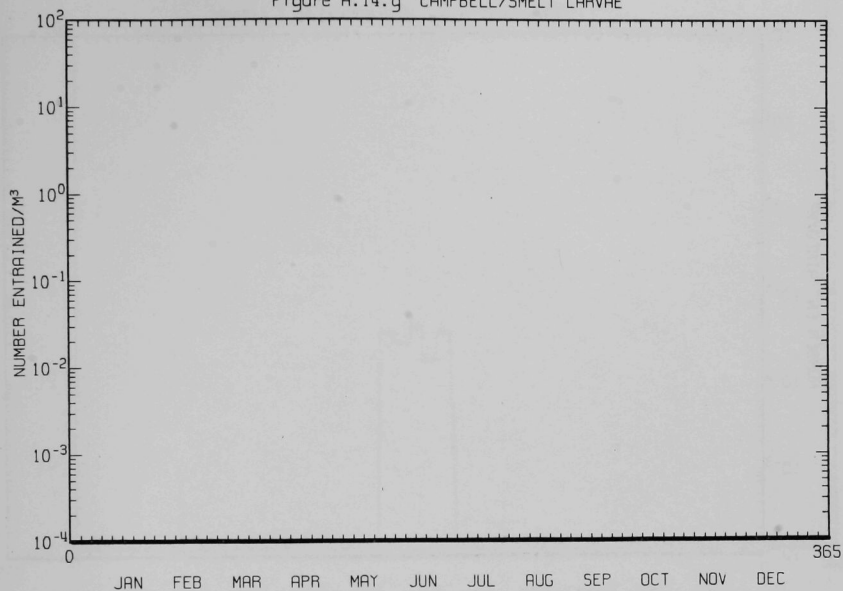


Figure A.15.g PALISADES/SMELT LARVAE

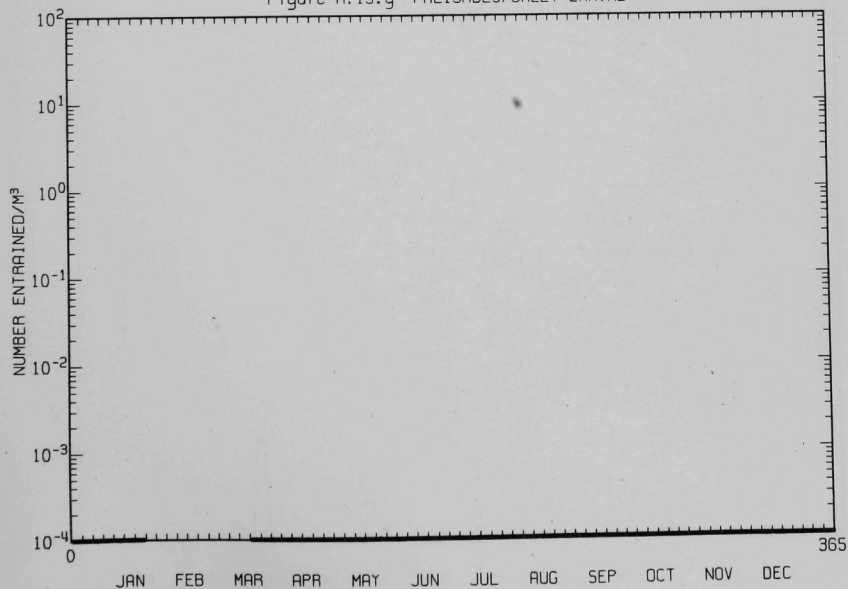


Figure A.16.g BIG ROCK/SMELT LARVAE

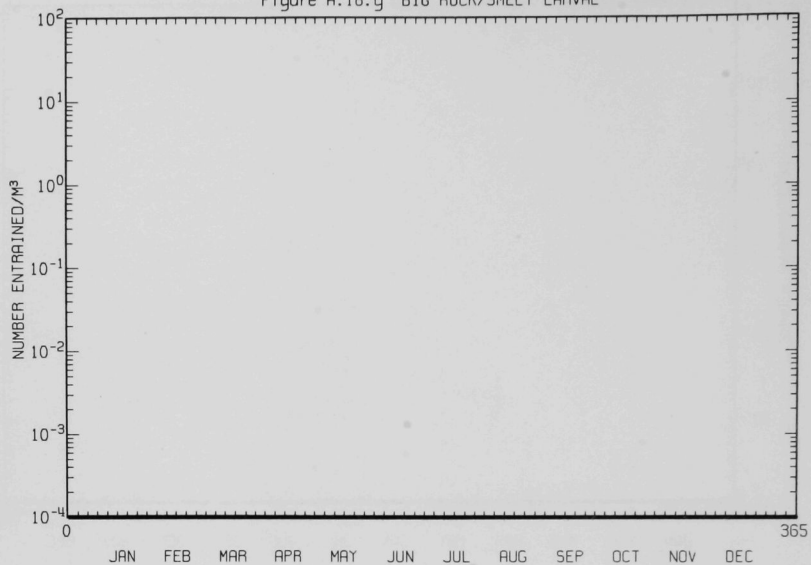


Figure A. 2.h D.C.COOK/Y.PERCH EGGS

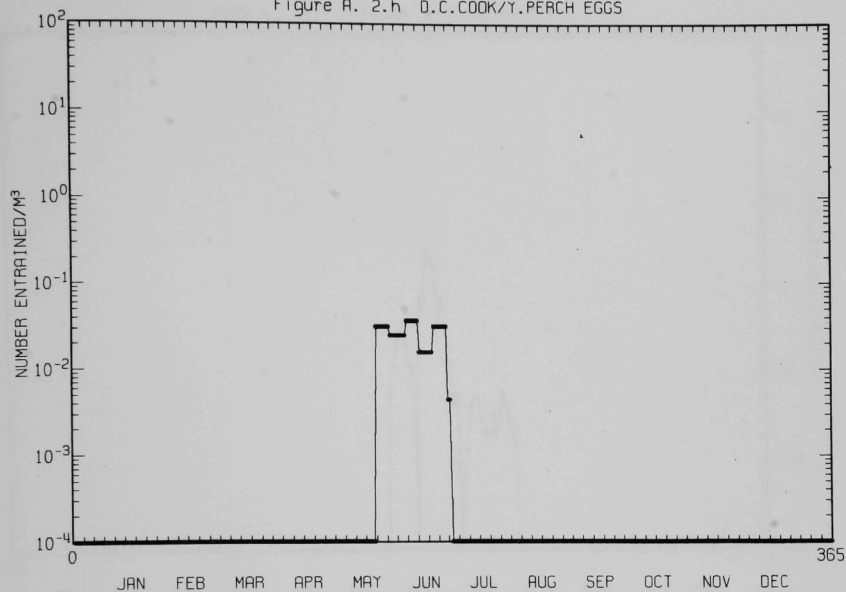


Figure A. 3.h BAILLY/Y.PERCH EGGS

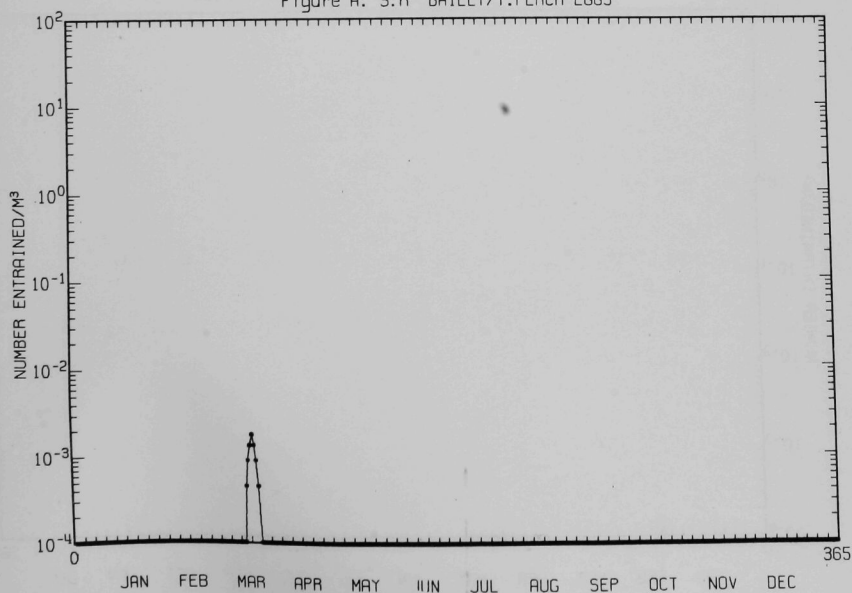


Figure A. 5.h PULLIAM/Y.PERC H EGGS

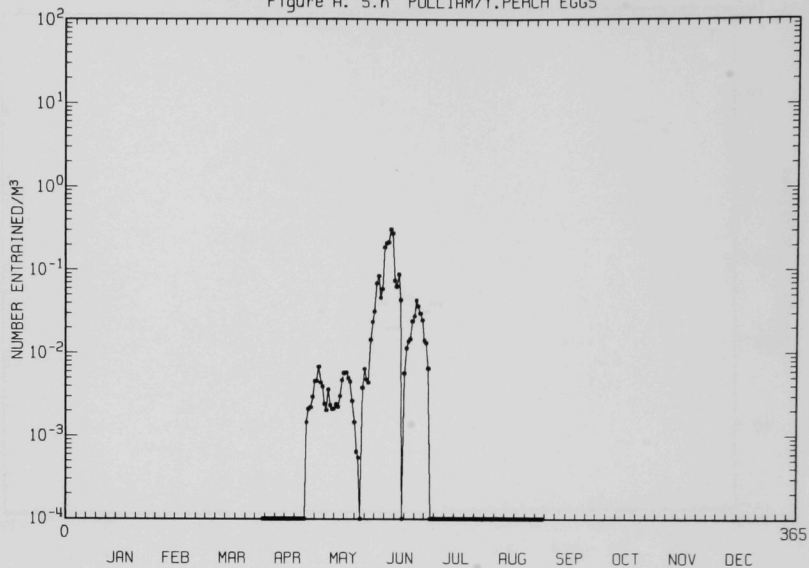


Figure A. 8.h PORT WASH/Y.PERC H EGGS

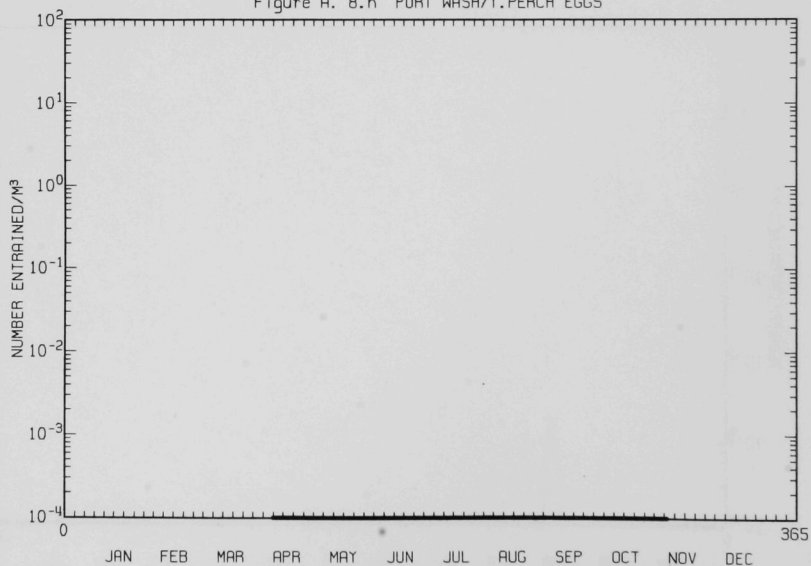


Figure A.14.h CAMPBELL/Y.PERCH EGGS

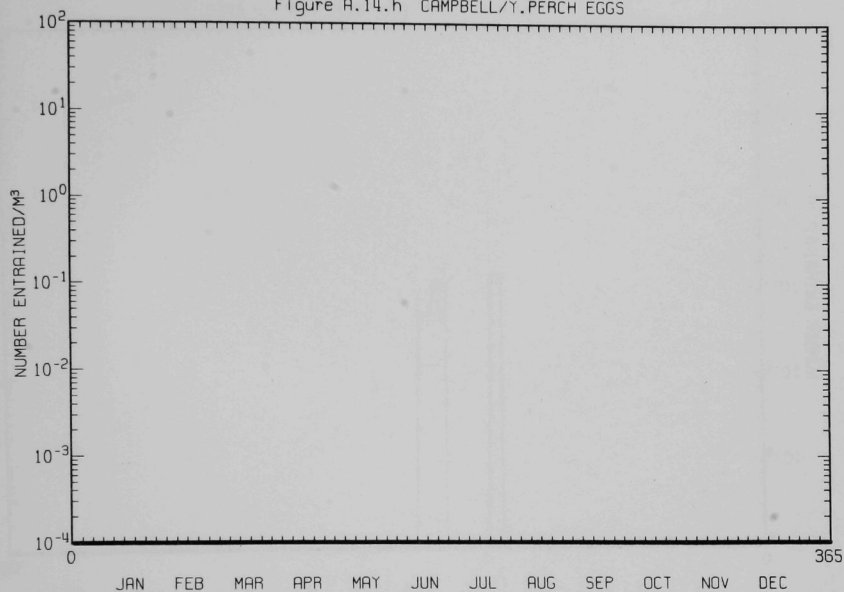
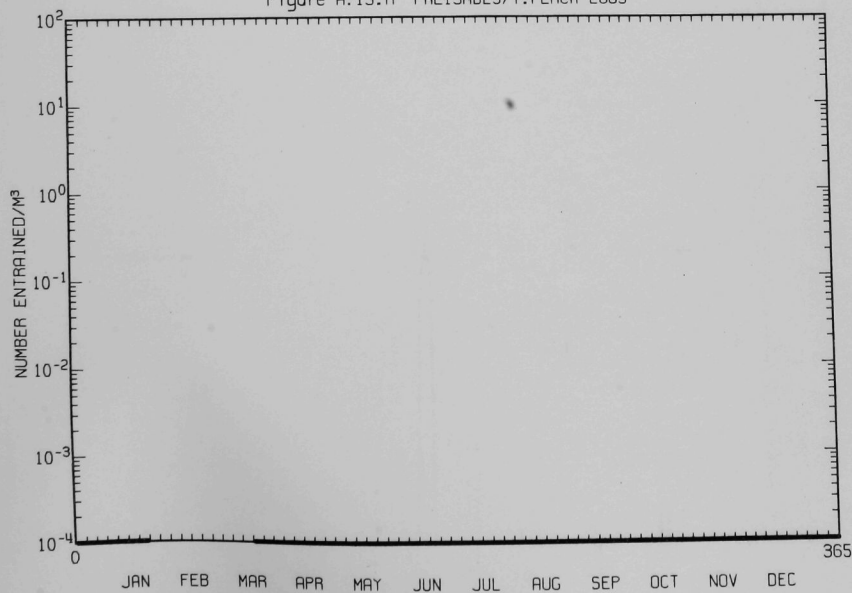


Figure A.15.h PALISADES/Y.PERCH EGGS



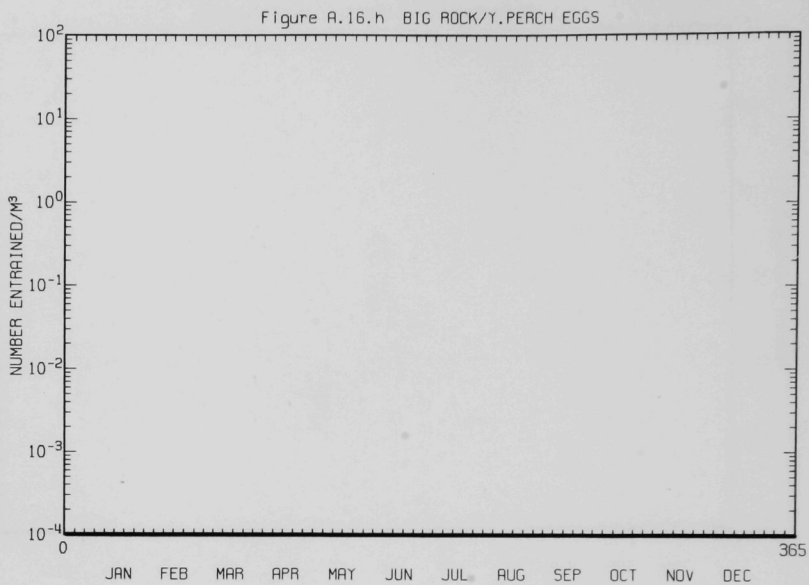


Figure A. 2.i D.C.COOK/Y.PERCH LARVAE

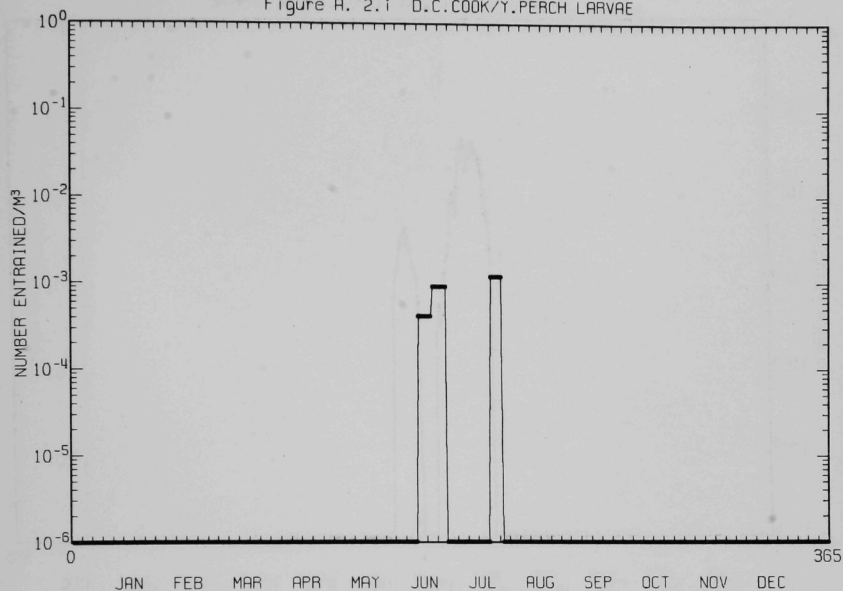


Figure A. 3.i BRILLY/Y.PERCH LARVAE

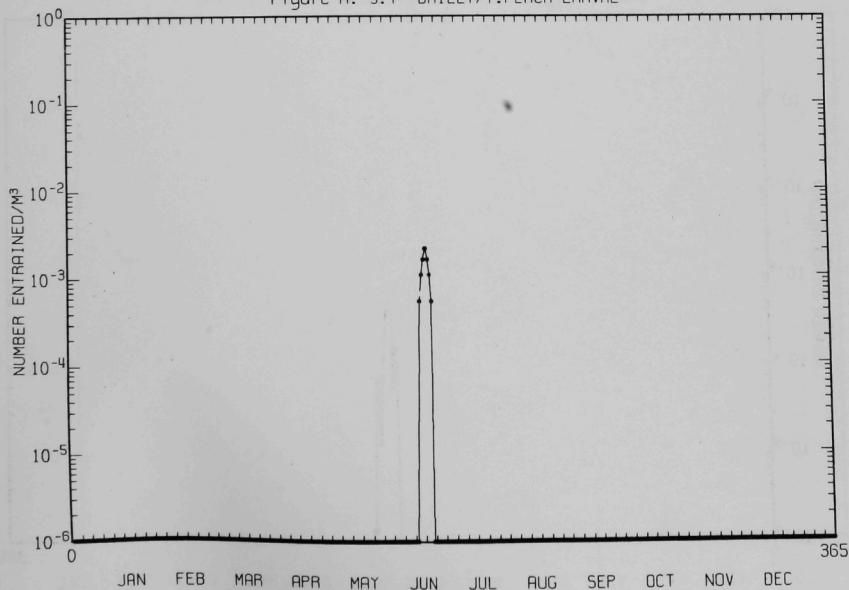


Figure A. 5.i PULLIAM/Y.PERCH LARVAE

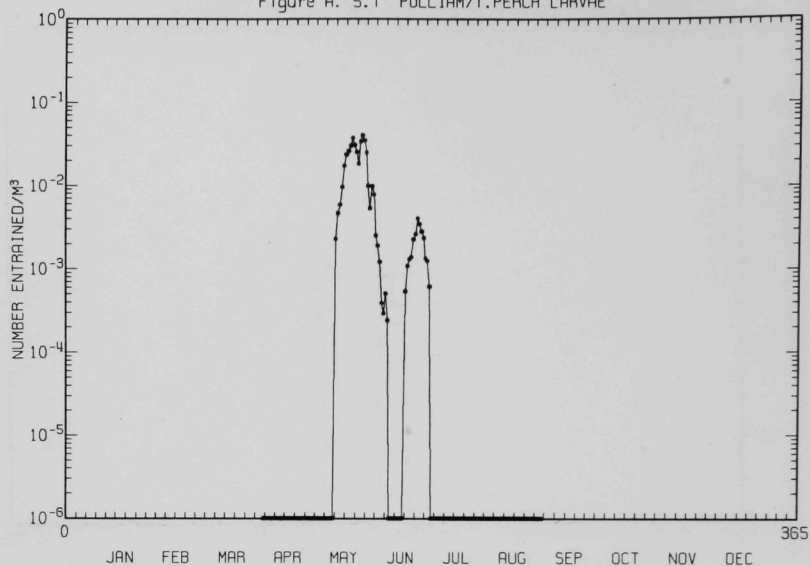


Figure A. 8.i PORT WASH/Y.PERCH LARVAE

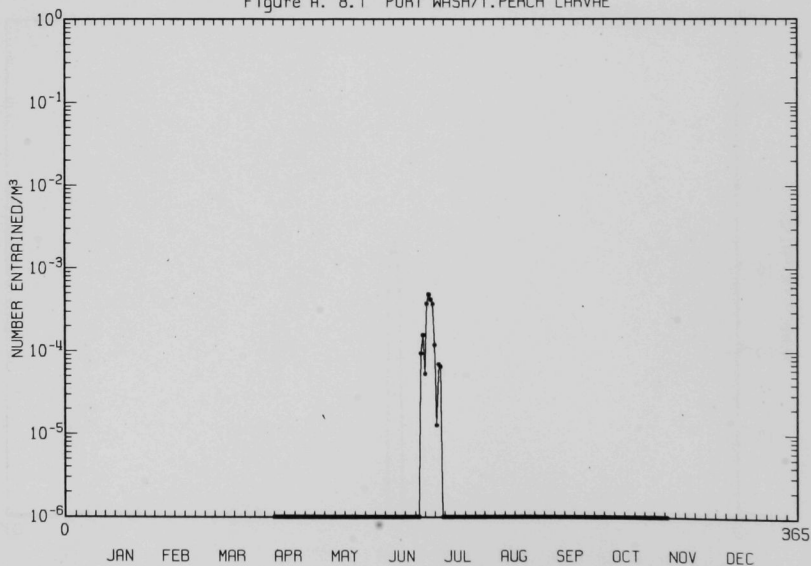


Figure A.14.i CAMPBELL/Y.PERCH LARVAE

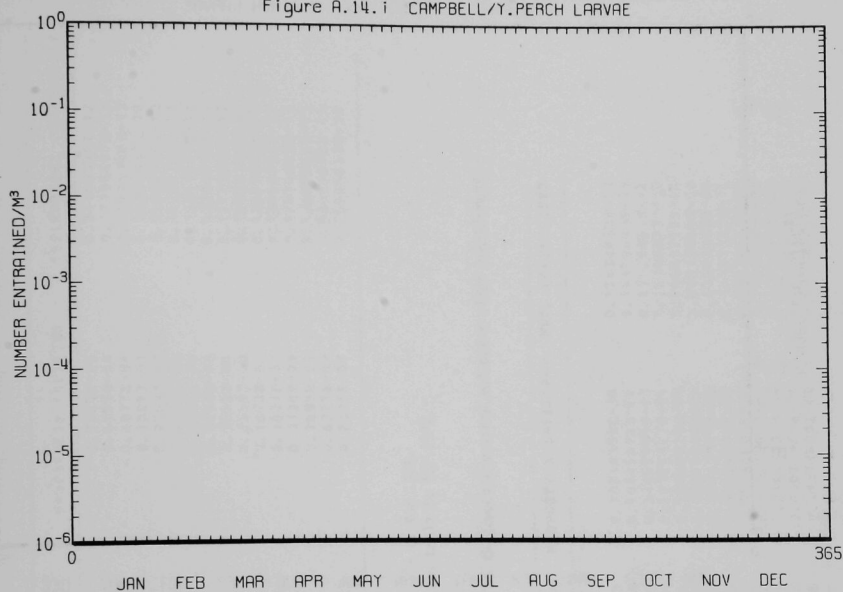


Figure A.15.i PALISADES/Y.PERCH LARVAE

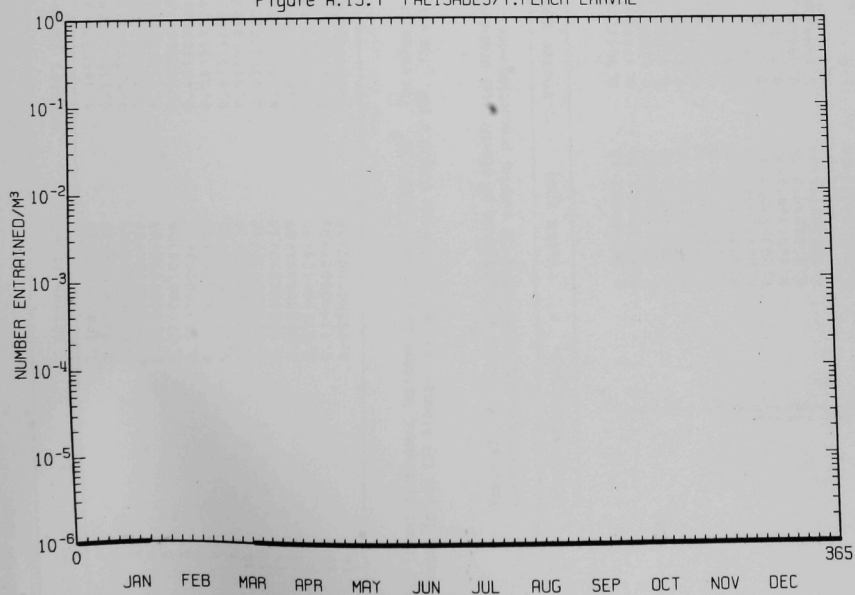


Figure A.16.i BIG ROCK/Y.PEARCH LARVAE

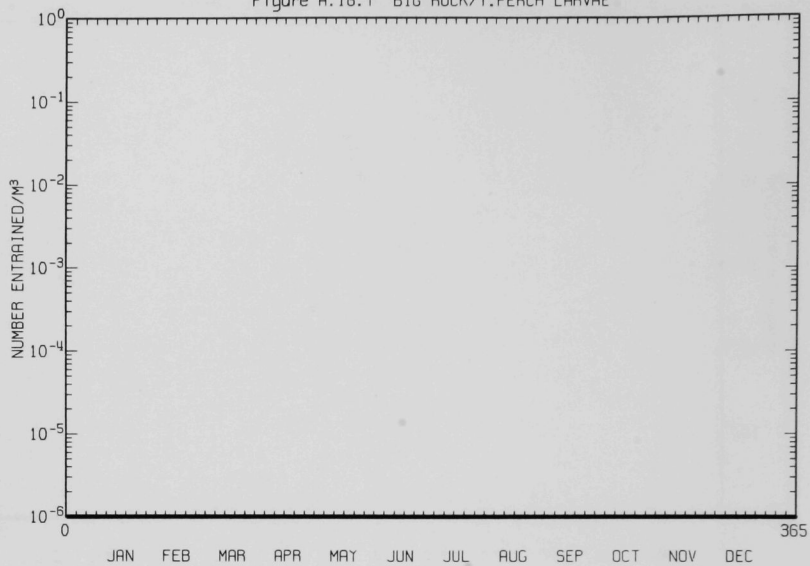


Table B1. Estimates of proportions of alewife standing stock impinged in 1975 and power plant impingement coefficients calculated using surplus production model.

POWER PLANT I. D.	VOLUME FLOW	BIOMASS IMPINGED	PROPORTION IMPINGED	IMPINGEMENT COEFFICIENT
1*	0.34814001E+10	0.14693706E+06	0.7347E-03	0.21103155E-12
2	0.32729001E+10	0.11590391E+05	0.5795E-04	0.17706607E-13
3	0.66949990E+09	0.57543711E+04	0.2877E-04	0.42975148E-13
4	0.59690010E+09	0.20072391E+05	0.1004E-01	0.16813867E-12
5	0.77470003E+09	0.41357129E+05	0.2068E-03	0.26692358E-12
6	0.82170010E+09	0.56296680E+04	0.2815E-04	0.34256218E-13
7	0.15320000E+10	0.38121164E+05	0.1906E-03	0.12441632E-12
8	0.10942999E+10	0.94791375E+05	0.4740E-03	0.43311432E-12
9	0.97340006E+09	0.31045945E+04	0.1552E-04	0.17733042E-13
10	0.24512000E+10	0.51005359E+05	0.2550E-03	0.10404161E-12
11**	0.14324001E+10	0.37437020E+05	0.1872E-03	0.13067932E-12
12	0.16513001E+10	0.36548961E+05	0.1827E-03	0.11066723E-12
13	0.82369997E+09	0.62559492E+04	0.3128E-04	0.17974689E-13
14	0.59690010E+09	0.15387852E+04	0.7694E-05	0.12989809E-13
15	0.11940000E+09	0.12758341E+02	0.6379E-07	0.53426878E-15
16	0.95500000E+08	0.47816925E+01	0.2391E-07	0.25035033E-15

* Zion (plant 1) biomass impinged in 1975 was 0.9532×10^6 . The value in the table is for 1974.

** Waukegan (plant 11) biomass impinged in 1975 was 0.4536×10^5 . The value in the table is for 1974.

Table B2. Estimates of proportions of alewife eggs produced in 1975 that were entrained and power plant entrainment coefficients calculated using the surplus production model.

POWER PLANT I. D.	VOLUME FLOW	NUMBER ENTRAINED	PROPORTION ENTRAINED	ENT. COEFFICIENT
1	0.34814001E+10	0.14137398E+10	0.38416852E-04	0.11034888E-13
2	0.32729001E+10	0.17000000E+10	0.46195666E-04	0.14114605E-13
3	0.66949990E+09	0.42201874E+09	0.11467905E-03	0.17129061E-12
4	0.59690010E+09	0.43163904E+09	0.11729327E-04	0.15140473E-13
5	0.77470003E+09	0.47349856E+08	0.12866813E-05	0.15658770E-14
6	0.82170010E+09	0.12441814E+06	0.12441814E-06	0.31212884E-16
7	0.15320000E+10	0.45745860E+07	0.10142719E-06	0.92686885E-16
8	0.10942999E+10	0.37325210E+07	0.14394811E-06	0.16481355E-15
9	0.97340006E+09	0.52972900E+07	0.25185000E-06	0.10274567E-15
10	0.24512000E+10	0.92680780E+07	0.10033793E-03	0.70090689E-13
11	0.14324001E+10	0.36946424E+10	0.21609230E-04	0.13086198E-13
12	0.16513001E+10	0.79521971E+09	0.10393469E-04	0.98457538E-13
13	0.82369997E+09	0.29844595E+10	0.38272603E-08	0.64118980E-17
14	0.59690010E+09	0.14084319E+06	0.0	0.0
15	0.11940000E+09	0.0	0.0	0.0
16	0.95500000E+08	0.0	0.0	0.0

Table B3. Estimates or proportions of alewife larvae produced in 1975 that were entrained and power plant entrainment coefficients calculated using the surplus production model.

POWER PLANT I.D.	VOLUME FLOW	NUMBER ENTRAINED	PROPORTION ENTRAINED	ENT. COEFFICIENT
1	0.34814001E+10	0.15972468E+08	0.43403503E-04	0.12467245E-15
2	0.32729001E+10	0.21000000E+09	0.57065301E-03	0.17435688E-14
3	0.66949990E+09	0.41615264E+08	0.11308512E-03	0.16890966E-14
5	0.77470003E+09	0.66691250E+05	0.18122648E-06	0.23393090E-17
6	0.82170010E+09	0.62247200E+06	0.16915019E-05	0.20585376E-16
7	0.15320000E+10	0.34300350E+06	0.93207609E-06	0.60840408E-17
8	0.10942999E+10	0.42359631E+06	0.11510783E-05	0.10518849E-16
9	0.87340006E+09	0.10956510E+07	0.29773164E-05	0.34088775E-16
10	0.24512000E+10	0.24778260E+07	0.67332321E-05	0.27469106E-16
11	0.14324001E+10	0.51204880E+08	0.13914390E-03	0.97140279E-15
12	0.16513001E+10	0.41444900E+07	0.11262217E-04	0.68202047E-16
13	0.82369997E+09	0.10098325E+08	0.27441129E-04	0.33314441E-15
14	0.59590010E+09	0.61564883E+04	0.16729611E-07	0.28027464E-18
15	0.11940000E+09	0.73131733E+01	0.19872770E-10	0.16643853E-20
16	0.95500000E+08	0.10062328E+02	0.27343322E-10	0.28631724E-20

Table B4. Estimates of proportions of yellow perch standing stock impinged in 1975 and power plant impingement coefficients calculated using the surplus production model.

POWER PLANT I. C.	VOLUME FLOW	BIOMASS IMPINGED	PROPORTION IMPINGED	IMPINGEMENT COEFFICIENT
1 *	0.34814001E+10	0.25907446E+03	0.2591E-04	0.74416723E-14
2	0.32729001E+10	0.96531714E+03	0.9693E-04	0.29616460E-13
3	0.66949990E+09	0.54530869E+02	0.5453E-05	0.81450180E-14
4	0.55690010E+09	0.82189819E+02	0.8219E-05	0.13769446E-13
5	0.77470003E+09	0.45766758E+04	0.4979E-03	0.64265851E-12
6	0.82170010E+09	0.44378845E+02	0.4438E-05	0.54008583E-14
7	0.15320000E+10	0.43168045E+02	0.4317E-05	0.28177578E-14
8	0.10942999E+10	0.46887146E+02	0.4689E-05	0.37363741E-14
9	0.87340006E+09	0.6319789E+01	0.6311E-06	0.72257628E-15
10	0.24512000E+10	0.15275256E+03	0.1528E-04	0.62317468E-14
11 **	0.14324001E+10	0.55464066E+02	0.5546E-05	0.38721061E-14
12	0.16513001E+10	0.10772827E+03	0.1077E-04	0.65238444E-14
13	0.82369997E+09	0.59553842E+02	0.5955E-05	0.72786049E-14
14	0.55690010E+09	0.11522538E+02	0.1192E-05	0.19974096E-14
15	0.11940000E+09	0.11647347E+00	0.1185E-07	0.99224020E-16
16	0.95500000E+08	0.2427201E+01	0.2421E-06	0.25347855E-14

* Zion (plant 1) biomass impinged in 1975 was 0.1420×10^3 . The value in the table is for 1974.

** Waukegan (plant 11) biomass impinged in 1975 was 0.6145×10^2 . The value in the table is for 1974.

Table B5. Estimates of proportions of yellow perch eggs produced in 1975 that were entrained and power plant entrainment coefficients calculated using the surplus production model.

POWER PLANT I.C.	VOLUME FLOW	NUMBER ENTRAINED	PROPORTION ENTRAINED	ENT. COEFFICIENT
1	0.34814001E+10	C.C	C.0	C.0
2	0.32729001E+10	0.18800000E+08	0.57566285E-C4	C.1758E775E-13
3	0.6694555CE+09	C.135E0836E+05	0.41585022E-07	0.62113561E-16
4	0.77470003E+09	0.45264220E+07	0.138ECC72E-C4	C.17890888E-13
5	0.8217CC1CE+09	0.0	0.0	0.0
6	0.1532000CE+10	C.C	C.C	C.C
7	0.10942995E+10	0.0	0.0	0.0
8	0.87340006E+09	C.0	0.0	0.0
9	0.2451200CE+10	0.0	C.0	0.0
10	0.14324001E+10	0.0	0.0	0.0
11	0.16513001E+10	C.C	C.C	0.0
12	0.82369997E+09	0.0	0.0	C.C
13	0.5569CC1CE+09	C.0	0.0	0.0
14	0.1194000CE+09	C.0	0.0	0.0
15	0.9550000CE+08	0.0	0.0	C.0
16				

Table B6. Estimates of proportion of yellow perch larvae produced in 1975 that were entrained and power plant entrainment coefficients calculated using surplus production model.

POWER PLANT I.C.	VOLUME FLOW	NUMBER ENTRAINED	PROPORTION ENTRAINED	ENT. COEFFICIENT
1	C.34814001E+10	C.C	0.0	0.0
2	0.32729001E+10	C.15E00000E+C6	0.46849207E-C4	0.14314269E-15
3	0.6694555CE+09	0.15528816E+05	0.47549856E-C5	C.71022879E-16
4	0.77470003E+09	C.51C21554E+C6	0.27871295E-C3	0.35976844E-14
5	0.82170010E+09	0.0	0.0	0.0
6	0.1532000CE+10	0.0	0.0	0.0
7	0.10942995E+10	C.6724E5E4E+C4	0.20591906E-05	0.18817406E-16
8	0.87340006E+09	0.0	0.0	C.C
9	0.2451200CE+10	C.C	0.0	0.0
10	0.14324001E+10	0.0	0.0	C.C
11	0.16513001E+10	0.0	0.0	0.0
12	0.82369997E+09	C.C	0.0	0.0
13	0.55690010E+09	0.0	C.C	C.C
14	0.1194000CE+09	C.C	0.0	0.0
15	0.9550000CE+08	C.0	0.0	0.0
16				

Table B7. Estimates of proportions of smelt standing stock impinged in 1975 and power plant impingement coefficients calculated using the surplus production model.

POWER PLANT I. D.	VOLUME FLOW	BIOMASS IMPINGED	PROPORTION IMPINGED	IMPINGEMENT COEFFICIENT
1 *	0.348140C1E+10	0.27409414E+05	0.1096E-02	C.31492425E-12
2	J.32729001E+10	0.11814774E+03	0.4726E-05	0.14439517E-14
3	0.66949990E+09	0.29758041E+02	C.1190E-05	C.17779266E-14
4	0.5569C010E+09	0.20418350E+02	0.8167E-06	C.13682928E-14
5	0.77470003E+09	0.87433838E+03	0.3497E-04	C.45144620E-13
6	0.82170010E+09	0.69506860E+03	0.2780E-04	C.33835632E-13
7	J.15320000E+10	0.13607659E+04	0.5443E-04	0.35529136E-13
8	0.10942999E+10	0.15913701E+04	0.6365E-04	C.58169398E-13
9	0.87340006E+09	0.75266027E+01	0.3011E-06	C.34470345E-15
10	0.24512000E+10	0.55522813E+04	0.2221E-03	0.90605095E-13
11 **	0.14324001E+10	0.27116650E+03	0.1085E-04	C.75723661E-14
12	0.16513001E+10	0.60069641E+02	0.2403E-05	C.14550872E-14
13	0.82369997E+09	0.54151020E+01	0.2166E-06	C.26296477E-15
14	0.5969C010E+09	0.16055588E+02	0.6422E-06	C.10759315E-14
15	0.11940000E+09	0.23694700E+00	0.9478E-08	0.79379229E-16
16	0.95500000E+08	0.29822702E+01	C.1193E-06	0.12491184E-14

* Zion (plant 1) biomass impinged in 1974 was 0.4263×10^4 . The values in the table are for 1974.

** Waukegan (plant 11) biomass impinged in 1975 was 0.5448×10^3 . The values in the table are for 1974.

Table B8. Estimates of proportions of smelt eggs produced in 1975 that were entrained and power plant entrainment coefficients calculated using the surplus production model.

POWER PLANT I.D.	VOLUME FLOW	NUMBER ENTRAINED	PROPORTION ENTRAINED	ENT. COEFFICIENT
1	0.34814001E+10	0.74355936E+C9	0.55421679E-03	0.15919368E-12
2	0.32729001E+10	0.75200000E+08	0.56047807E-04	0.17124814E-13
3	0.66949990E+09	0.45243650E+07	0.33720835E-05	0.50367222E-14
5	0.77470003E+09	0.76767190E+07	0.57215857E-C5	0.73855479E-14
6	0.82170010E+09	0.49827080E+07	0.37136942E-C5	0.45195239E-14
7	0.15320000E+10	0.0	0.0	0.0
8	0.10942999E+10	0.24584688E+06	0.18323374E-C6	C.16744383E-15
9	0.87340006E+09	C.C	0.0	0.0
10	0.24512000E+10	0.10CC8956E+C6	0.74598404E-07	0.30433417E-16
11	0.14324001E+10	0.23360851E+09	0.17411230E-C3	C.12155283E-12
12	0.16513001E+10	0.31467616E+08	0.23453322E-04	0.14202950E-13
13	0.82369997E+09	0.21424140E+07	0.15967762E-C5	0.19385416E-14
14	0.5969C010E+09	0.0	0.0	0.0
15	0.11940000E+C9	0.0	0.0	0.0
16	0.95500000E+08	0.0	0.0	0.0

Table B9. Estimates of proportions of smelt larvae produced in 1975 that were entrained and power plant entrainment coefficients calculated using the surplus production model.

POWER PLANT I.D.	VOLUME FLOW	NUMBER ENTRAINED	PROPORTION ENTRAINED	ENT. COEFFICIENT
1	0.34814001E+10	0.11920482E+08	0.88945403E-03	0.25519599E-14
2	0.32729001E+10	0.24400000E+07	0.18185742E-03	0.55564557E-15
3	0.66949990E+09	0.31374588E+06	0.23384011E-04	0.34527573E-15
5	0.77470003E+09	0.13520088E+06	0.10076756E-04	0.13007287E-15
6	0.82170010E+09	0.10189205E+08	0.75941905E-03	0.52420375E-14
7	0.15320000E+10	0.19427820E+07	0.14479891E-03	0.54516150E-15
8	0.10942995E+10	0.43049138E+06	0.32085256E-04	0.29320321E-15
9	0.87340006E+09	0.0	0.0	0.0
10	0.24512000E+10	0.66567890E+07	0.49614185E-03	0.20240761E-14
11	0.14324001E+10	0.18272669E+06	0.13618936E-04	0.95077648E-16
12	0.16513001E+10	0.10883388E+06	0.81115768E-05	0.49122313E-16
13	0.82369997E+09	0.98598770E+07	0.73755672E-03	0.89541818E-14
14	0.59690010E+09	0.24755967E+03	0.18480861E-07	0.30961370E-18
15	0.11940000E+09	0.14613811E+02	0.10891925E-08	0.91222047E-19
16	0.95500000E+08	0.52509033E+03	0.39135891E-07	0.40979950E-17

Table B10. Estimates of proportions of alewife standing stock impinged in 1975 and power plant impingement coefficients calculated using the dynamic pool model.

POWER PLANT I. D.	VOLUME FLOW	BIOMASS IMPINGED	PROPORTION IMPINGED	IMPINGEMENT COEFFICIENT
1*	0.34814001E+10	0.14693706E+06	0.6189E-03	0.17778427E-12
2	0.32729001E+10	0.11590391E+05	0.4882E-04	0.14916992E-13
3	0.66949990E+09	0.57543711E+04	0.2424E-04	0.35204570E-13
5	0.59690010E+09	0.20072391E+05	0.8455E-04	0.14164895E-12
6	0.77470003E+09	0.41357129E+05	0.1742E-03	0.22487063E-12
7	0.82170010E+09	0.56296680E+04	0.2371E-04	0.23859273E-13
8	0.15320000E+10	0.38121164E+05	0.1606E-03	0.10481497E-12
9	0.10942995E+10	0.94791375E+05	0.3993E-03	0.36437865E-12
10	0.87340006E+09	0.31045945E+04	0.1308E-04	0.14972961E-13
11**	0.24512000E+10	0.51005359E+05	0.2148E-03	0.87650210E-13
12	0.14324001E+10	0.37437020E+05	0.1577E-03	0.11009124E-12
13	0.16513001E+10	0.36548961E+05	0.1540E-03	0.93232008E-13
14	0.82369997E+09	0.62559492E+04	0.2635E-04	0.31991906E-13
15	0.59690010E+09	0.15387852E+04	0.6482E-05	0.1085964E-13
16	0.11940000E+09	0.12758341E+02	0.5374E-07	0.45009658E-15
16	0.95500000E+08	0.47816925E+01	0.2014E-07	0.21090856E-15

* Zion (plant 1) biomass impinged in 1975 was 0.9532×10^6 . The value in the table is for 1974.

** Waukegan (plant 11) biomass impinged in 1975 was 0.4536×10^5 . The value in the table is for 1974.

Table B11. Estimates of proportions of alewife eggs produced in 1975 that were entrained and power plant entrainment coefficients calculated using the dynamic pool model.

POWER PLANT I. D.	VOLUME FLOW	NUMBER ENTRAINED	PROPORTION ENTRAINED	ENT. COEFFICIENT
1	0.34814001E+10	0.14137398E+10	0.84987143E-03	0.24411777E-12
2	0.32729001E+10	0.17000000E+10	0.10219573E-02	0.31224838E-12
3	0.66949990E+09	0.42201874E+10	0.25369711E-02	0.37893525E-11
5	0.77470003E+09	0.41163904E+09	0.25948021E-03	0.33494301E-12
6	0.82170010E+09	0.47349856E+09	0.28464419E-04	0.34640900E-13
7	0.15320000E+10	0.45785860E+07	0.27524229E-05	0.17966208E-14
8	0.10942999E+10	0.37325210E+07	0.22438098E-05	0.20504525E-14
9	0.87340006E+09	0.52972900E+07	0.31844729E-05	0.36460635E-14
10	0.24512000E+10	0.92680780E+07	0.55715172E-05	0.22729754E-14
11	0.14324001E+10	0.36946424E+10	0.22210393E-02	0.15505713E-11
12	0.16513001E+10	0.79521971E+09	0.47804718E-03	0.28949759E-12
13	0.82369997E+09	0.29844595E+10	0.17941117E-02	0.21781127E-11
14	0.59690010E+09	0.14084319E+06	0.94658045E-07	0.14184631E-15
15	0.11940000E+09	0.0	0.0	0.0
16	0.95500000E+08	0.0	0.0	0.0

Table B12. Estimates of proportions of alewife larvae produced in 1975 that were entrained and power plant entrainment coefficients calculated using the dynamic pool model.

POWER PLANT I. D.	VOLUME FLOW	NUMBER ENTRAINED	PROPORTION ENTRAINED	ENT. COEFFICIENT
1	0.34814001E+10	0.15972468E+08	0.96018799E-03	0.27580492E-14
2	0.32729001E+10	0.21000000E+09	0.12624189E-01	0.38571858E-13
3	0.66949990E+09	0.41615264E+08	0.25017096E-02	0.37366804E-13
5	0.77470003E+09	0.66691250E+05	0.40091572E-05	0.51751080E-16
6	0.82170010E+09	0.62247200E+06	0.37420017E-04	0.45539710E-15
7	0.15320000E+10	0.34300350E+06	0.20619715E-04	0.13459335E-15
8	0.10942999E+10	0.42359631E+06	0.25464571E-04	0.23270155E-15
9	0.87340006E+09	0.10956510E+07	0.65865272E-04	0.75412402E-15
10	0.24512000E+10	0.24778260E+07	0.14895499E-03	0.60768134E-15
11	0.14324001E+10	0.51204880E+08	0.30781913E-02	0.21489724E-13
12	0.16513001E+10	0.41444900E+07	0.24914672E-03	0.15087904E-14
13	0.82369997E+09	0.10098325E+08	0.60706260E-03	0.73699422E-14
14	0.59690010E+09	0.61564883E+04	0.37039846E-06	0.62003366E-17
15	0.11940000E+09	0.73131733E+01	0.43963277E-09	0.36820132E-19
16	0.95500000E+08	0.10062328E+02	0.60439880E-09	0.63340115E-19

Table B13. Estimates of proportions of yellow perch standing stock impinged in 1975 and power plant impingement coefficients calculated using the dynamic pool model.

POWER PLANT I.C.	VOLUME FLOW	BIOMASS IMPINGED	PROPORTION IMPINGED	IMPINGEMENT COEFFICIENT
1*	0.34814001E+10	0.25907446E+03	0.2578E-C4	0.74057243E-14
2	0.32729001E+10	0.96531714E+03	0.9646E-04	0.29473392E-13
3	0.66949990E+09	0.54520869E+02	0.5427E-C5	0.81056716E-14
5	0.77470003E+09	0.82189819E+02	0.8179E-05	0.10557998E-13
6	0.82170010E+05	0.45766758E+04	0.4955E-03	0.60297259E-12
7	0.15320000E+10	0.44378845E+02	0.4416E-05	0.28827987E-14
8	0.10942999E+10	0.43168045E+02	0.4296E-05	0.39257504E-14
9	0.87340006E+05	0.40887146E+02	0.4069E-05	0.46587591E-14
10	0.24512000E+10	0.63109789E+01	0.6280E-C6	0.25622111E-15
11**	0.14324001E+10	0.15275256E+03	0.1520E-04	0.10612584E-13
12	0.16513001E+10	0.55464066E+02	0.5520E-05	0.33425870E-14
13	0.82365557E+05	0.16772827E+03	0.1072E-04	0.13015403E-13
14	0.59690010E+09	0.55553842E+02	0.5566E-C5	0.99956800E-14
15	0.11940000E+05	0.11522538E+02	0.1186E-C5	0.99371398E-14
16	0.95500000E+08	0.11847347E+02	0.1179E-07	0.12345673E-15

* Zion (plant 1) biomass impinged in 1975 was 0.1420×10^3 . The value in the table is for 1974.

** Waukegan (plant 11) biomass impinged in 1975 was 0.6145×10^2 . The value in the table is for 1974.

Table B14. Estimates of proportions of yellow perch eggs produced in 1975 that were entrained and power plant entrainment coefficients calculated using the dynamic pool model.

POWER PLANT I.C.	VOLUME FLOW	NUMBER ENTRAINED	PROPORTION ENTRAINED	ENT. COEFFICIENT
1	0.34814001E+10	0.0	0.0	0.0
2	0.32729001E+10	0.18800000E+08	0.24184586E-03	0.72893420E-13
3	0.66949990E+09	0.13500000E+05	0.17470575E-C6	0.26094968E-15
5	0.77470003E+09	0.45264220E+07	0.58228528E-C4	0.75162641E-13
6	0.82170010E+05	0.0	0.0	0.0
7	0.15320000E+10	0.0	0.0	0.0
8	0.10942999E+10	0.0	0.0	0.0
9	0.87340006E+05	0.0	0.0	0.0
10	0.24512000E+10	0.0	0.0	0.0
11	0.14324001E+10	0.0	0.0	0.0
12	0.16513001E+10	0.0	0.0	0.0
13	0.82365557E+05	0.0	0.0	0.0
14	0.59690010E+09	0.0	0.0	0.0
15	0.11940000E+05	0.0	0.0	0.0
16	0.95500000E+08	0.0	0.0	0.0

Table B15. Estimates of proportions of yellow perch larvae produced in 1975 that were entrained and power plant entrainment coefficients calculated using the dynamic pool model.

POWER PLANT I.D.	VOLUME FLOW	NUMBER ENTRAINED	PROPORTION ENTRAINED	ENT. COEFFICIENT
1	0.34814001E+10	C.C	0.C	0.0
2	0.32729001E+10	0.15300000E+C6	0.19682158E-C3	0.6136671E-15
3	0.66949990E+C9	0.15528E16E+05	0.19976505E-04	0.25837921E-15
5	0.77470003E+C9	0.91021554E+C6	0.11709211E-02	0.15114493E-13
6	0.82170010E+C9	0.0	0.0	0.C
7	0.15320000E+10	C.C	0.0	0.0
8	0.10942999E+10	0.67248584E+C4	0.86510145E-C5	0.75055147E-16
9	0.87340000E+C9	0.0	0.0	0.0
10	0.24512000E+10	C.C	C.C	0.C
11	0.14324001E+10	0.0	0.0	0.C
12	0.16513001E+10	C.C	0.0	0.C
13	0.82369997E+C9	C.C	0.0	0.C
14	0.59690010E+C9	0.0	0.0	0.C
15	0.11940000E+C9	C.C	0.0	0.0
16	0.95500000E+08	0.0	0.0	0.0

Table B16. Estimates of proportions of smelt standing stock impinged in 1975 and power plant impingement coefficients calculated using the dynamic pool model.

POWER PLANT I. C.	VOLUME FLOW	BIOMASS IMPINGED	PROPORTION IMPINGED	IMPINGEMENT COEFFICIENT
1*	0.34814001E+10	0.27409414E+05	0.1110E-02	0.31877665E-12
2	0.32729001E+10	0.11814774E+03	0.4784E-C5	0.14616174E-14
3	0.66949990E+C9	0.29758041E+02	0.1205E-05	0.17996765E-14
4	0.59690010E+09	0.20418350E+02	0.8267E-06	0.13850321E-14
5	0.77470003E+09	0.87433838E+03	0.3540E-C4	0.45696902E-13
6	0.82170010E+C9	0.69506860E+03	0.2814E-04	0.34249571E-13
7	0.15320000E+10	0.13607659E+04	0.5510E-04	0.35963786E-13
8	0.10942999E+10	0.15913701E+04	0.6443E-04	0.5888104E-13
9	0.87340000E+09	0.75266027E+01	0.3047E-06	0.34892040E-15
10	0.24512000E+10	0.55522813E+04	0.2248E-03	0.91713529E-13
11**	0.14324001E+10	0.27116650E+03	0.1098E-04	0.76650044E-14
12	0.16513001E+10	0.60069641E+02	0.2432E-05	0.14728882E-14
13	0.82369997E+09	0.54151020E+01	0.2193E-06	0.26618180E-15
14	0.59690010E+09	0.16055588E+02	0.6501E-06	0.10890940E-14
15	0.11940000E+09	0.23654700E+00	0.9594E-08	0.80350326E-16
16	0.95500000E+08	0.29822702E+01	0.1208E-06	0.12643995E-14

* Zion (plant 1) biomass impinged in 1975 was 0.4263×10^4 . The value in the table is for 1974.

** Waukegan (plant 11) biomass impinged in 1975 was 0.5448×10^3 . The value in the table is for 1974.

Table B17. Estimates of proportions of smelt eggs produced in 1975 that were entrained and power plant entrainment coefficients calculated using the dynamic pool model.

POWER PLANT I.D.	VOLUME FLOW	NUMBER ENTRAINED	PROPORTION ENTRAINED	ENT. COEFFICIENT
1	0.34814001E+10	0.74359536E+09	0.16500093E-01	0.47394996E-11
2	0.32729001E+10	0.75200000E+08	0.16686500E-02	0.50983832E-12
3	0.66949900E+09	0.45243650E+07	0.10039337E-03	0.14995280E-12
5	0.77470003E+09	0.76767190E+07	0.17034251E-03	0.21988195E-12
6	0.82170010E+09	0.49827080E+07	0.11056376E-03	0.13455491E-12
7	0.15320000E+10	0.0	0.0	0.0
8	0.10942999E+10	0.24584688E+06	0.54552174E-05	0.49851209E-14
9	0.87340006E+09	0.0	0.0	0.0
10	0.24512000E+10	0.10008956E+06	0.22209360E-05	0.90606098E-15
11	0.14324001E+10	0.23360851E+09	0.51836520E-02	0.36188596E-11
12	0.16513001E+10	0.31467616E+08	0.69825049E-03	0.42284893E-12
13	0.82369997E+09	0.21424140E+07	0.47539070E-04	0.57714033E-13
14	0.59690010E+09	0.0	0.0	0.0
15	0.11940000E+09	0.0	0.0	0.0
16	0.95500000E+08	0.0	0.0	0.0

Table B18. Estimates of proportions of smelt larvae produced in 1975 that were entrained and power plant entrainment coefficients calculated using the dynamic pool model.

POWER PLANT I.D.	VOLUME FLOW	NUMBER ENTRAINED	PROPORTION ENTRAINED	ENT. COEFFICIENT
1	0.34814001E+10	0.11920482E+08	0.26450977E-01	0.75977852E-13
2	0.32729001E+10	0.24400000E+07	0.54142401E-02	0.16542625E-13
3	0.66949900E+09	0.31374588E+06	0.69618691E-03	0.10398603E-13
5	0.77470003E+09	0.13520088E+06	0.30000415E-03	0.38725161E-14
6	0.82170010E+09	0.10189205E+08	0.22609357E-01	0.27515316E-12
7	0.15320000E+10	0.19427820E+07	0.43109395E-02	0.28139261E-13
8	0.10942999E+10	0.43049138E+06	0.95523964E-03	0.87292200E-14
9	0.87340006E+09	0.0	0.0	0.0
10	0.24512000E+10	0.66567890E+07	0.14771093E-01	0.60260553E-13
11	0.14324001E+10	0.18272669E+06	0.40546176E-03	0.28306429E-14
12	0.16513001E+10	0.10883388E+06	0.24149715E-03	0.14624651E-14
13	0.82369997E+09	0.9858770E+07	0.21958474E-01	0.26658309E-12
14	0.59690010E+09	0.24795967E+03	0.55021059E-06	0.92177947E-17
15	0.11940000E+09	0.14613811E+02	0.32427344E-07	0.27158548E-17
16	0.95500000E+08	0.52509033E+03	0.11651500E-05	0.12200512E-15

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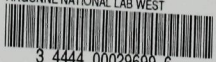
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W. K. Sinclair
R. E. Rowland
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M. M. Thommes (10)
S. A. Spigarelli (10)
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A. K. Blackadar, Pennsylvania State University
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16. ABSTRACT A large volume of water is withdrawn from Lake Michigan for cooling and other industrial and municipal purposes. Potential ecological impacts of such withdrawals have caused concern. This study estimates the impacts of entrainment and impingement at water intakes on alewife, smelt, and yellow perch populations of Lake Michigan. Impingement and entrainment estimates were based on data collected by utilities for 316(b) demonstrations at 16 power plants. Two conventional fishery stock assessment models, the surplus production model and the dynamic pool model, were applied to assess the impacts. Fisheries data were applied to estimate the model parameters. Movements related to spawning and seasonal habitat selection cause high variation in impingement and entrainment over time and location. Impingement and entrainment rates were related to geographic location, intake type and position, and volume of water flow. Although the biomass impinged and numbers entrained are large, the proportions of the standing stocks impinged and the proportions of the eggs and larvae entrained are small. The reductions in biomass assuming full flow at all intakes and our estimates of biomass in 1975 are predicted by the models to be: 2.86% for alewife, 0.76% for smelt, and 0.28% for yellow perch.		
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